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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A comparison is made of the results of aerial target vulnerability assessments of two typical targets (bomber and fighter), attacked by two warheads (surface-air missile and AAA projectile) using the Swedish model, Luft Mals Program No. 3 (LMP-3), and the U.S. Reference Model (REFMOD). The results of these computer runs are compared, as are results of similar computer runs of fragments along parallel trajectories from four attack aspects.

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PREFACE

This program was a cooperative effort of personnel from the Swedish National Defense Research Institute (Försvarets Forskningsanstalt of FOA) and Southwest Research Institute (SwRI). This program was partially funded by the U.S. Army Materiel Systems Analysis Activity (AMSAA) under Contract DAAK11-79-C-0059 and partially funded by FOA.

In conducting this program, the principal author, Mrs. Ingrid M. Gyllenspetz, was resident at SwRI in San Antonio, TX for fourteen months. We wish to express our great appreciation to the individuals who made this extended visit of Mrs. Gyllenspetz and, therefore, this program possible:

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Mr. Åke Persson, FOA
Mr. Alex B. Wenzel, SwRI.

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Mr. Orlando T. Johnson, USABRL
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Dr. Benjamin E. Cummings, AMSAA
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Mr. Thomas L. Wasmund, NSWC, Dahlgren, VA
Mr. Gerald B. Bennett, Jr., ASD, Wright-Patterson AFB, OH
Capt. John F. Calvert, USN, DDT&E
Mr. Melvin H. Keith, NWC, China Lake, CA.

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Mr. Thomas Gilbert, ASI
Mr. John E. Musch, ASI.

Many individuals at SwRI contributed to the success of this program. In particular, we wish to thank:

Dr. Wilfred E. Baker for his guidance and advice throughout the program,
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Mr. Van B. Parr for his assistance in describing the statistical analysis,
Mr. Clark R. Charbonnet for preparing a minicomputer program which helped mechanize the similitude modeling effort, and
Ms. Deborah J. Stowitts for assistance in editing this report.

We realize there are many others whom we have not named who also assisted us. To all of these individuals we also wish to express our appreciation.

The technical monitor for this program was Dr. Benjamin E. Cummings and the alternate was Mr. Nicolas Hagis. We wish to express our appreciation to these gentlemen for their assistance and guidance.

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1.0 INTRODUCTION

This project was conducted at Southwest Research Institute (SwRI) under Contract DAAK11-79-C-0059 from the Army Materiel Systems Analysis Activity (AMSAA). Support for this program was provided by the Swedish National Defense Research Institute (Försvarets Forskningsanstalt-FOA), funded by Sweden, and Armament Systems, Incorporated (ASI), funded by AMSAA.

1.1 PURPOSE

The United States Government has developed sophisticated methods of vulnerability assessment for aircraft, supporting the methodology development by many tests. The Swedish defense establishment has developed a different vuln rability assessment methodology which lacks many of the refinements of the American methodologies and uses a much smaller data base of test results. Th program offers the U.S. insight into a simpler methodology which has a potential for developing a more economical aerial target vulnerability assessment methodology, and offers Sweden the opportunity to compare their simpler methodology to the more complex U.S. methodologies with the potential to improve their detailed techniques and assumptions, thus providing improvements which would otherwise require extensive tests.

1.2 BASES FOR COMPARISON

Sweden does not develop or support numerous vulnerability/survivability computer programs. However, for detailed calculations of warheads effects, four different, but somewhat similar methodologies have been developed. The reason is that, depending on the weapon system and/or the target, different effects are important and therefore different assumptions and simplifications can be made. Their four methodologies and their computer programs are listed in Table 1, with most attention being paid to aerial targets. These models are used by FOA, other Swedish Government organizations and the Swedish defense industries.

The vulnerability assessment community in the U. S. is many times larger than that of Sweden. The U. S. has many Army, Navy and Air Force laboratories and many defense industries and research organizations involved in vulnerability assessments [1]. Coordination of the assessment

Table 1. Swedish Vulnerability Assessment Methodologies

Purpose	Computer Programs Involved: From Target Acquisition, Trajectory to Target Neighborhood	Computer Programs Involved: Target Neighborhood to Burst Point	Computer Programs Involved: Burst Point Through Target Response	Total Assessment Includes
Aerial Targets	Several antiaircraft missile & antiaircraft artillery programs prepared for different weapons systems	LMP11-Contact Fuze LPF1-Laser Proximity Fuze ZEVS-Radar Proximity Fuze Vilma - A simplified model under development	LMP-3-Burst point to weapon effects Part II-Weapon effects to target response	Accounts for fast target speed; mostly for fragments but has some blast effects (HE warheads); evaluates aircraft completion of mission and immediate availability for subsequent missions.
Surface Targets Less Armored (Ships, Parked Aircraft, Light Equipment)		Verksam - locates burst point and determines effect upon components Verana - determines vehicle response		Used with stationary or slowly moving targets; mostly for fragments but has some blast effects (HE warheads); evaluates utility of target and when available if damaged; computes probability that elapsed repair time is greater than X hours.
Armored Targets (Tanks, APC's, Armored Ships)	Dirikaneld (Direct Fire)	APAS - Geometric Description of Target - Effects on Critical Components - Target Response		Used with stationary or slowly moving targets; for KE or HEAT projectiles or mines; no repair time consideration; has immediate and delayed kills; evaluates mobility and fire power
Artillery vs Light Surface Targets	AVM -			All targets represented by boxes; considers effect of vegetacion and snow; treats fragment damage only; fuzes may be superquick, delay or proximity.

methodologies used is made through two separate groups: (1) The Joint Technical Coordination Group for Munitions Effectiveness (JTCG/ME), generally responsible for coordinating procedures by which the effectiveness of U.S. munitions against hostile targets can be gaged; and (2) The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), generally responsible for developing design criteria and improving technology to increase the survivability of aircraft [2]. The most effective coordination between these two groups has been achieved simply because the members of a subcommittee of one group are generally also members of the subgroup of the other group. For example, most of the government laboratory representatives in the Aerial Target Vulnerability Assessment Subcommittee of the JTCG/ME are also members of the Vulnerability Assessment Subgroup of the JTCG/AS. These subcommittees/subgroups are most effective in assuring that common assessment criteria are used and in keeping their home laboratories/organizations informed of the results from efforts in other organizations within the vulnerability assessment community. The committee organization is loose enough that it does not stifle initiative in the many organizations involved either in developing new assessment methodologies or techniques or in using and improving the existing assessment methodologies; but, the organization is close enough that the lessons learned or innovations made by almost any member of the community are soon common knowledge.

1.2.1 Computer Models Selected

Recently within the U.S., a single joint-service approved computer model has been prepared for the anti-air end game situation. This model is named the Reference Model or REFMOD [3], and it is intended to serve as a reference to which other similar models can be compared. This model was deemed the most appropriate to use for comparing results with the Swedish ATV model, LMP-3 [4]. The associated computer models which are needed to implement fully an aerial target vulnerability assessment for the Swedish methodology and for REFMOD are shown in Figure 1. The tables of vulnerable areas required for REFMOD can be generated using COVART [5], VAREA [6], POINT BURST or manual techniques. Where COVART or VAREA is used, a shotline generator program, such as SHOTGEN [7], GIFT [8], or FASTGEN [9] for single fragments is used with the target description as an

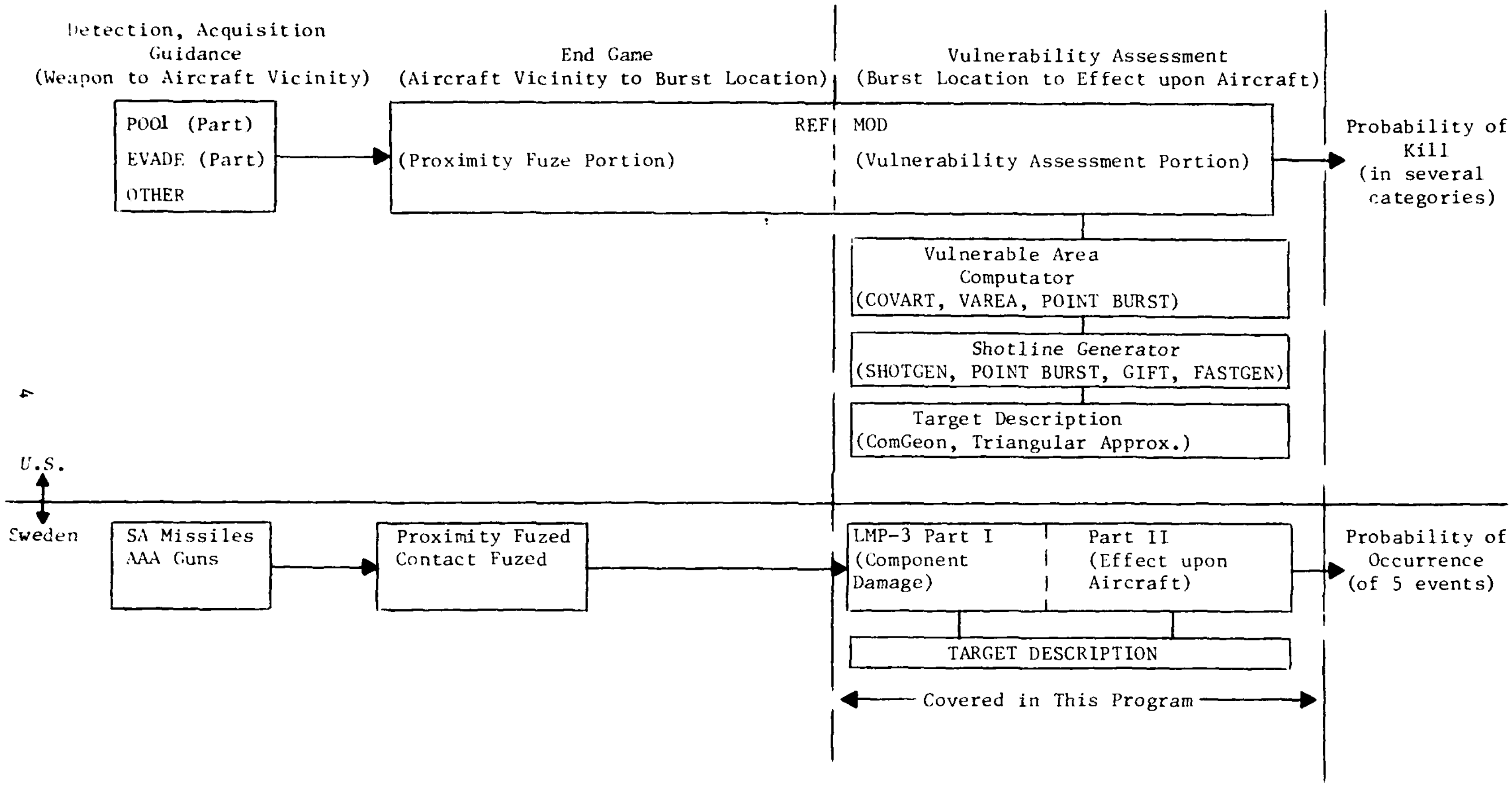


Figure 1. ATV Assessment Methodologies

input. For those computer programs, the mathematical models have been compared and some comparative runs have been made.

1.3 CLARIFICATION OF TERMINOLOGY

This section is necessary since this project involves two nationalities, speaking different languages, where many of the readers of this report are dependent upon translations. Each nationality has developed its own terminology. When a term is translated, the connotation of the term may differ greatly from that of the user.

1.3.1 Target Description

In both Sweden and the U.S., the term "target description" is applied to the data describing the target mathematically for the computer programs used. However, the mathematical operations performed are so different that the same term has completely different connotations in the two countries. In the U.S., the "target description" is a set of data describing mathematically the geometry (shape and location) of components of an aircraft and is input in shotline generation programs. The description is very detailed as not only the critical components are described but also all that can retard fragments. Furthermore, a very accurate geometric representation is used. An explanation of U. S. target description techniques is given in Appendix A.

The Swedish target description consists of both geometrical and physical data. The geometric description is not detailed because very simplified geometric bodies are used and only the critical components are described. Physical data, such as weight density and other material properties, are included as necessary for the penetration calculations. In the target description, data are also included by which the effect of the damage to the components will affect the aircraft capability to perform its assigned mission. Appendix B contains a more complete explanation of Swedish target description data.

1.3.2 Vulnerable Area

The term "vulnerable area" also has completely different connotations in the U.S. and in Sweden. In the U. S., the definition of "vulnerable area" is:

"A quantitative measure of the ballistic vulnerability of a target element expressed in real dimensions (square feet, square meters, etc.). Typically, the vulnerable area of a target in a plane normal to the trajectory of the ballistic threat mechanism, and the probability of kill of that component given a hit on the target by the ballistic threat mechanism" [10].

In Sweden, the term "vulnerable area" denotes the area which a component presents to an impacting fragment, which area, if hit, could result in the loss of the component function. This area does not include any effect from shielding. This area is currently scalar, since the area is assumed to be the same irrespective of direction (aspect). However, the vulnerable area is not necessarily that presented, since the analyst may deem that only a given fraction of the presented area may be vulnerable. This vulnerable area is the mean of the area presented in three orthogonal directions multiplied by the fractional vulnerability.

1.3.3 Damage Criteria

The third term which has different connotations for aerial targets in Sweden and the U.S. is the damage criteria. In the U.S., the damage criteria are established for components or systems [11]. These criteria relate levels of damage to degradation of component performance. Examples of these are the amount of material which must be removed from a drive shaft for failure, the total area removed from a combustor wall to assure engine malfunction, and the hole sizes in fuel tanks or lines to assure engine starvation within a specified time period. In each case, the component or system failure to function is related to physical damage and the physical damage is related to threat terminal effects, primarily to fragment impact but also to blast and fire.

For each type component or assembly, component failure to operate is predicted by calculating mechanical phenomena such as area of material removed or kinetic energy or momentum imparted per unit area, and relating these to damage. Each aircraft kill level is related through the damage criteria to these component failures.

In Swedish methodology, the damage criteria are not applied to components but to aircraft systems. Malfunctions such as fuel leakage, landing gear inoperability, missile fire direction, control loss, etc.,

are defined for each system. Probabilities are then applied to each malfunction. Four probabilities are given to determine whether the mission is aborted and the aircraft lost or not, or the mission completed and the aircraft lost or not. Those probabilities are termed "damage criteria" and the sum of them has to be unity by definition. For other targets, damage criteria are used in the same way in Sweden as in the U.S.

1.3.4 Target Kill Categories/Kill Levels

The categories used in each country are defined somewhat differently. To help understand the relationships between the attrition and mission kill, a generalized Venn diagram is used (Figure 2). This Venn diagram may represent the relative probability of loss, damage or mission abort of a single aircraft for a single encounter or mission, or of an aircraft assigned to a single mission. Let us treat the single aircraft, single mission or encounter situation. The attrition circle represents the probability of loss of the aircraft. The mission kill circle represents the probability of the aircraft failing to complete the mission (mission abort). The circle enclosing the two circles represents unity; the area outside of the attrition and mission kill circles represents the probability that the aircraft will be available for a subsequent mission but might or might not need repairs first. Time is important! If attrition does not occur the aircraft must be capable of flying for the time needed to reach a friendly landing site. To complete the mission, the aircraft must be able to fly to the designated target. But, for some damage there is no time-dependence. Those systems which make it possible to land or deliver weapons must be functioning, otherwise no mission will be completed or no aircraft will return.

For comparing the results of a vulnerability assessment made using the Swedish methodology to one using the American methodology, one can compare the attrition aspects, the mission aspects and the intersections, provided that the appropriate data exist and that the assumed time relationships are equal or that the components considered are comparable.

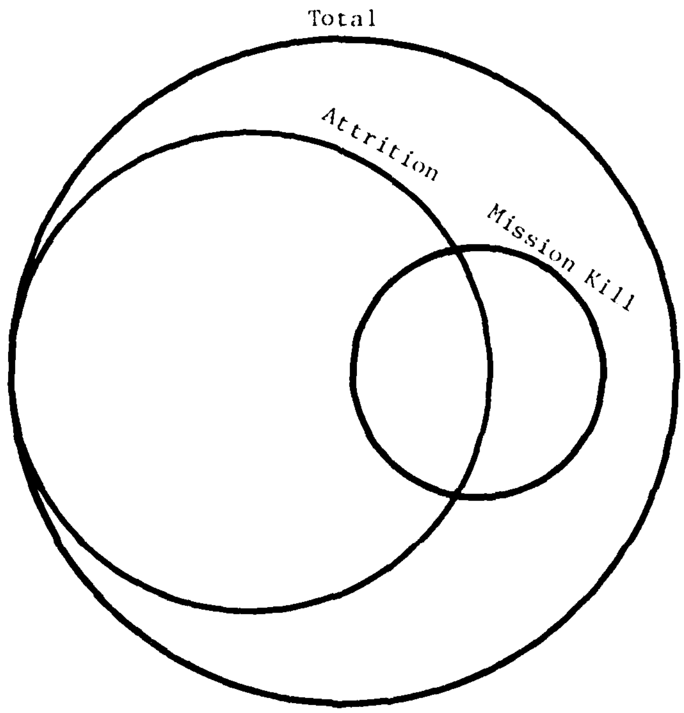


Figure 2. Generalized Venn Diagram of Aircraft Vulnerability

2.0 DESCRIPTION OF SWEDISH METHODOLOGY

2.1 GENERAL

The Swedish programs for aerial target vulnerability have been used to evaluate the effectiveness of the design of HE warheads used against aircraft; to evaluate vulnerability hardening concepts for aircraft; to evaluate fuze and warhead design and sizing for surface-to-air (SA) missiles; to trade-off use of SA missiles and antiaircraft artillery (AAA) guns and mixtures thereof for protection of Army installations; to evaluate the effectiveness of naval antimissile defenses; and to support the evaluation for purchases of SA missile systems.

A computer program called LMP-3 [4] is used to calculate the effect of a warhead against an aircraft given a burst point. The burst point can be either internal or external, but has to be given as input data by coordinates.

2.2 LOGIC

In addition to burst point data, target data and warhead data have to be given (Figure 3). The target data include geometric and physical data for the aircraft with regard to its components, together with an analysis of the consequences of damages upon the target's various functional systems.

The warhead data describe fragments, their number, mass and velocity. The size of a zone around the burst point is given to describe the blast effect. The computer program determines whether a given critical component is in a region where it is subjected to damage either from fragment impact or blast.

Results of these computations have been presented in different ways, depending upon whether the application in question dealt with warheads which burst within targets or outside of targets. Nevertheless, in either case, the probabilities for the various events occurring have been computed for each burst.

With regard to bursts within the target, a mean value is determined for a number of bursts, which constitute a given tactical encounter. The number of bursts used for a single encounter depends upon the statistical accuracy desired.

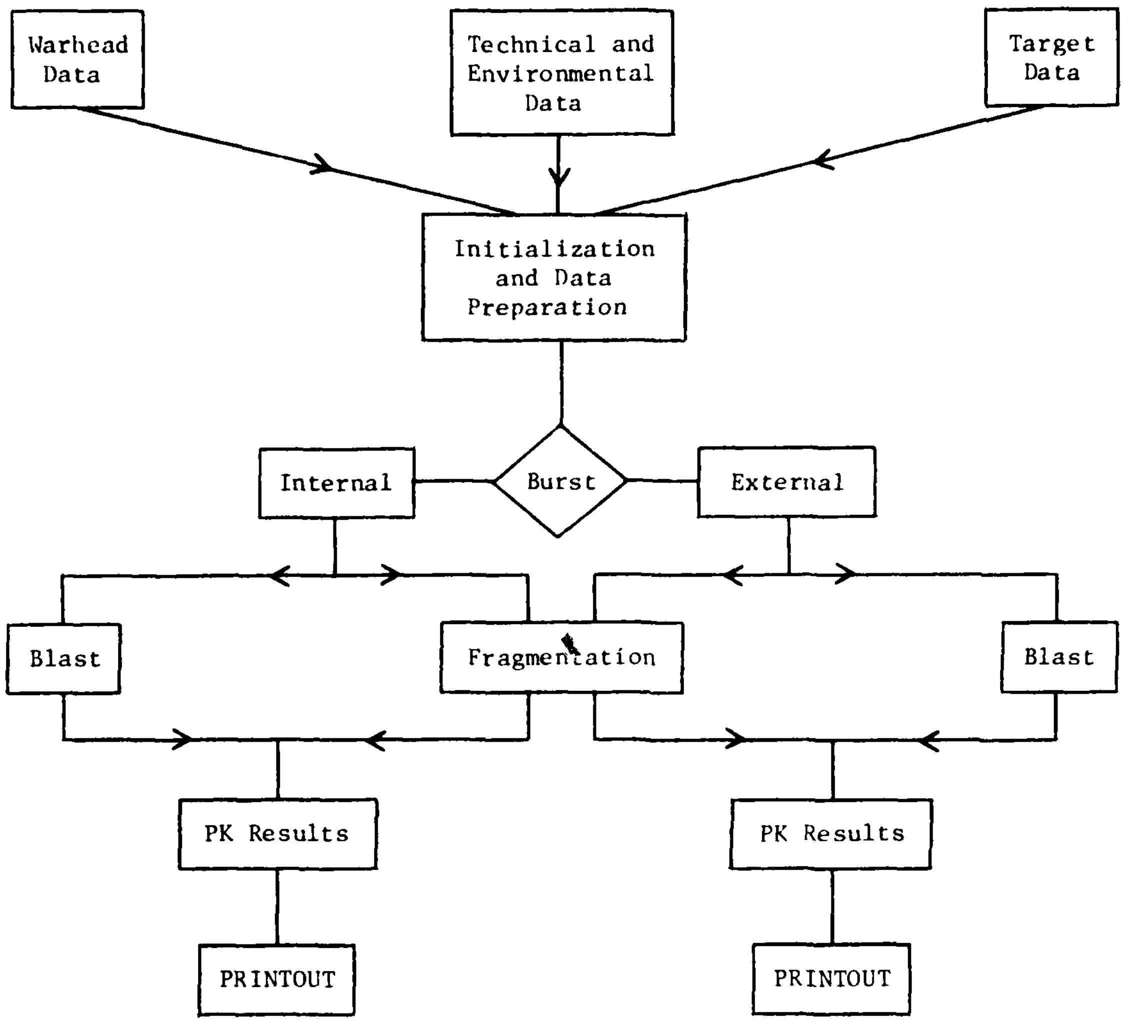


Figure 3. LMP-3 Main Structure

The results for warheads bursting outside of targets (when the warhead's triggering range was not known) have been presented as lines of isoprobabilities (curves which connect points of bursts yielding the same probabilities). The effects from the points of burst in a given plane have been computed in a grid system, and isoprobability curves in this plane have been drawn.

2.3 EVENT CATEGORIES (SIMILAR TO KILL LEVELS)

If the target is an aircraft or a helicopter, the following resultant events can be used as effect criteria:

Event 1 - Mission aborted. Aircraft/helicopter lost.

Event 2 - Mission aborted. Aircraft/helicopter returns to base. Subsequent missions delayed.

Event 3 - Mission accomplished. Aircraft/helicopter lost.

Event 4 - Mission accomplished. Aircraft/helicopter returns to base. Subsequent missions delayed until damage is repaired.

Event 5 - Mission accomplished. No damage to vital components noted. Aircraft/helicopter returns to base.

The sum of the probabilities of these five events is 1; Event 5 includes undamaged as well as damaged aircraft. The events are time-dependent but that is related to the mission, which includes tactical and environmental data for the aircraft in question.

Tactical data include:

Type of mission
Armament alternatives
Distance to target specified in mission
Distance to home base
Altitude
Velocity
Additional performance data

Environmental data include:

Day or night
Meteorological conditions
Visibility
Season

The five events can be combined. For example, the sum of the probability

of Events 1 and 3 equal the probability that the aircraft is lost, either immediately or on the way back to the base. Similarly, the sum of Events 1 and 2 is the probability that the mission was aborted.

The Swedish mission/availability events are illustrated in Figure 4. Event 1 (mission aborted, aircraft lost) is the intersection of the attrition and mission circles. Event 2 (mission aborted, aircraft returned in damaged condition) is the mission circle less the intersection with the attrition circle. Event 3 (mission completed, aircraft lost) is the attrition circle less the intersection with the mission circle. Events 4 and 5 (mission completed, aircraft returned) are outside the attrition and mission circles (the problem of predictive aircraft battle damage repair is not treated in LMP-3).

The tactical data make it possible to establish the times from the threat impact to arrival at the target site, for return to the base and for travel to some other friendly landing place. Rotary-wing aircraft are treated the same as fixed-wing aircraft.

2.4 TARGET DESCRIPTION TECHNIQUES

A Swedish target description is made to support a much different series of calculations than is an American target description. The Swedish target description is specifically directed toward a given mission and a given encounter situation, even though there are many items which would be invariant in a target description prepared for the same aircraft for other missions and other situations. The factors which make this target description mission and encounter specific are the selection of functional subsystems and the dependence upon the time from encounter to subsystem failure which is built into the probabilities for the first four mission/availability events.

From drawings, the target's external surfaces are described as a number of simple bodies. Individual bodies represented by polyhedra with a suitable number of corners are selected to have a density which is as homogeneous as possible.

Skin thickness and internal densities (which are used to indicate fragment retardation during penetration of the structure) are indicated for the various polyhedra making up the target.

Using handbooks and other similar information, the critical components of the target are described.

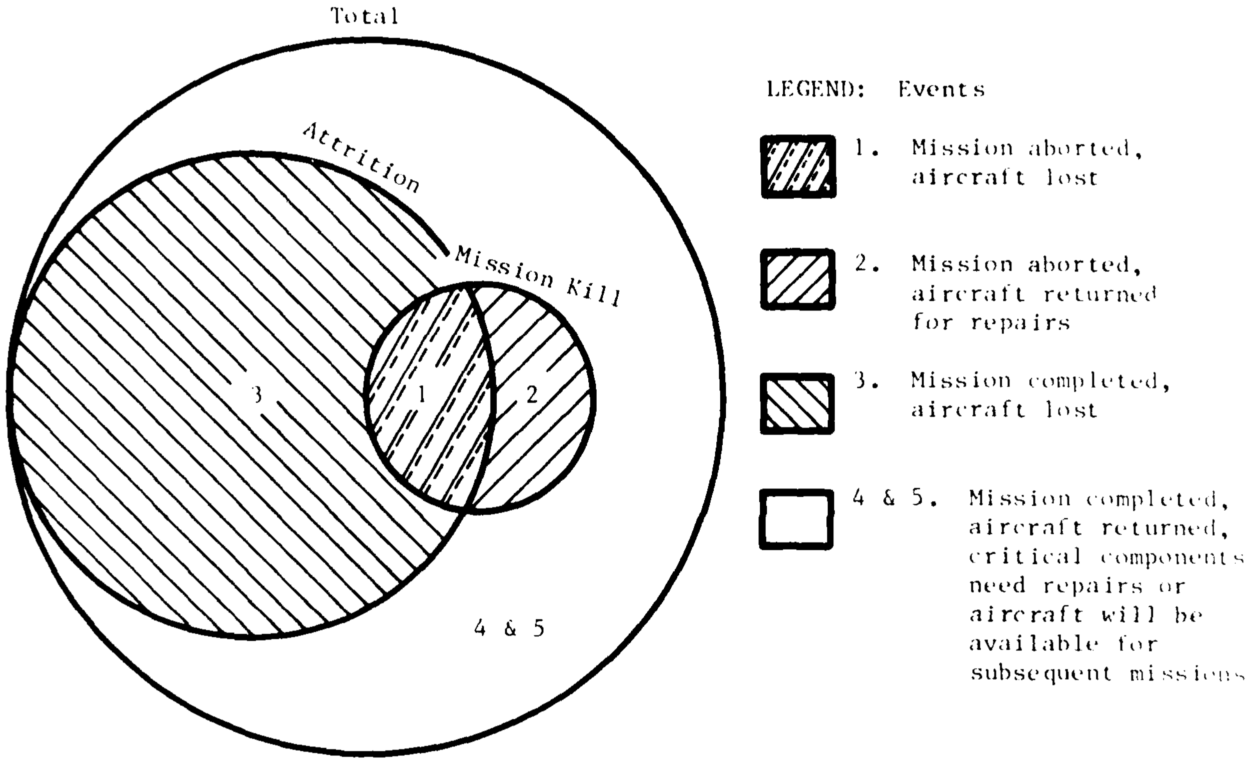


Figure 4. Venn Diagram of Swedish Vulnerability Events

This description is designed to determine the degradation in performance and condition occurring in aircraft critical systems as a consequence of the damage suffered by various components struck by fragments (by analysis of aircraft operational functions).

The target is divided into a number of functional systems which are evaluated with regard to both design and function. Redundant systems are treated. The components of a system are analyzed assuming that the system's function is affected by single fragment impacts. This analysis has been carried out in cooperation with designers and manufacturing personnel, and is based upon experience from testing of the effects from fragment impacts [12]. When fragments strike the components of a system, various types of damage occur, causing the system in question to fail to function. The malfunctions which do not result in immediate loss of the aircraft and which are detectable to a pilot (indicator lights in the cockpit or erratic or abnormal functioning of some equipment the pilot can see during normal flight) are evaluated by conferring with an appropriate number of pilots. The pilots who are familiar with that or similar aircraft determine whether they would continue or abandon the mission.

In principle, the analyses include all of the vital (critical) components in the target, and give, for each possible component damage, the failure modes which would occur. Those components of a functional system which, when they are damaged, cause the same kind of failure are gathered into subsystems or systems.

2.5 CHARACTERIZATION OF WARHEADS

Warhead data are based upon experimental investigations performed at FOA. In these investigations, the fragmentation from the shell or missile or warhead including fragment size and number in various ejection areas and at varying ejection velocities is determined. As a minimum, three real warheads are tested. One is used to obtain the size and number of fragments. For this experiment, a test pit filled with sawdust is used [13]. One warhead is detonated surrounded by witness plates to show the directions in which the fragments are ejected. The fragment velocities are determined by photographing a detonation with either a high-speed camera or flash x-ray equipment.

Programs have also been developed to compute the warhead data for a warhead for which only blueprints are available, based upon the empirical data mentioned above.

The warhead is described with a number of cones (with common symmetry axes) within which the fragments travel. The cones are selected so that the fragment velocities will be approximately constant between two adjacent cones. Within each zone the velocity, mass distribution, and spread of the fragments are defined. Spoke warheads cannot be treated and continuous-rod warheads are treated with difficulty.

2.6 TERMINAL EFFECTS

The number of effective fragment impacts upon each component is calculated in the Swedish model. These calculations are made for air drag, the fragment retardation in the structure, and the position of the component within the fragment zone at the moment of impact. The number of effective fragment impacts upon all components of a given functional system are summed and then used to predict the probability that the total system damage will cause the loss of the aircraft or an incomplete mission. Each aircraft attrition/mission event is related through the damage criteria to the total number of effective fragment impacts upon all components at a functional system. Redundant functional systems can be treated and there is also a difference between systems which are rendered inoperable by one fragment and systems for which the kill probability increases with the number of hits.

In addition to damage from impacting fragments, the program treats damage from blast. Blast damage is treated a little differently dependent upon whether the burst is internal or external. If the burst is external but within a given distance, the parameters used to compute the momentum reduction factor for fragments impacting critical components within given polyhedra are changed. These changes are made also if the burst is internal. Furthermore, if the burst point is within a specific area such as fuel cells, cabin or cockpit, engine or inlet, that volume is treated as a separate subsystem with its own effect criteria. If any component is within a blast effect ellipsoid for the warhead, the component is assumed totally damaged.

The results from each run of the program (for a given warhead detonating at a given burst point against a given aircraft) are the probabilities of all five events (see Section 2.3). No Monte-Carlo technique is used, so the results will be exactly the same if the run is repeated.

3.0 DESCRIPTION OF COMPARABLE U.S. METHODOLOGY

3.1 GENERAL

In the U.S. there are many different computer programs that can be used to calculate the effect of a warhead against an aircraft. The program which was used in this comparison is REFMOD, the JTCG/ME-sponsored End-Game Reference Model. As this program needs input data (vulnerable areas) produced by other programs (see Figure 1) some of these are briefly described. COVART, SHOTGEN and FASTGEN have been used as examples.

3.2 LOGIC

Not all the facilities of REFMOD have been used in this comparison because the burst points have been given as input data (see Figure 5).

The REFMOD target P_k results from applying one or more of the following damage mechanisms:

- Direct hit, regardless of warhead detonation against:
  - a. Target composed of truncated elliptical cones
  - b. Target composed of ellipsoids
  - c. Target composed of polygonal surfaces
- Blast, propagating through the air as a pressure wave
- Warhead fragments, striking components which are:
  - a. Structural
    - Damaged by area removal
    - Cylindrical, damaged by energy density
  - b. Systems components
    - Cylindrical, cut or sprayed by particles
    - Critical spherical, sprayed by particles
    - Critical linear, cut by particles
    - Planar, cut or sprayed by particles

A combinatorial description of the target is available to compute the resulting P_k sustained by the target because of damage to its interrelated components and systems.

The missile involves descriptions of three systems which define its functional characteristics:

- Physical shape, for direct hits
- The fuze, for determining detonation point
- The warhead, for blast and fragment damage

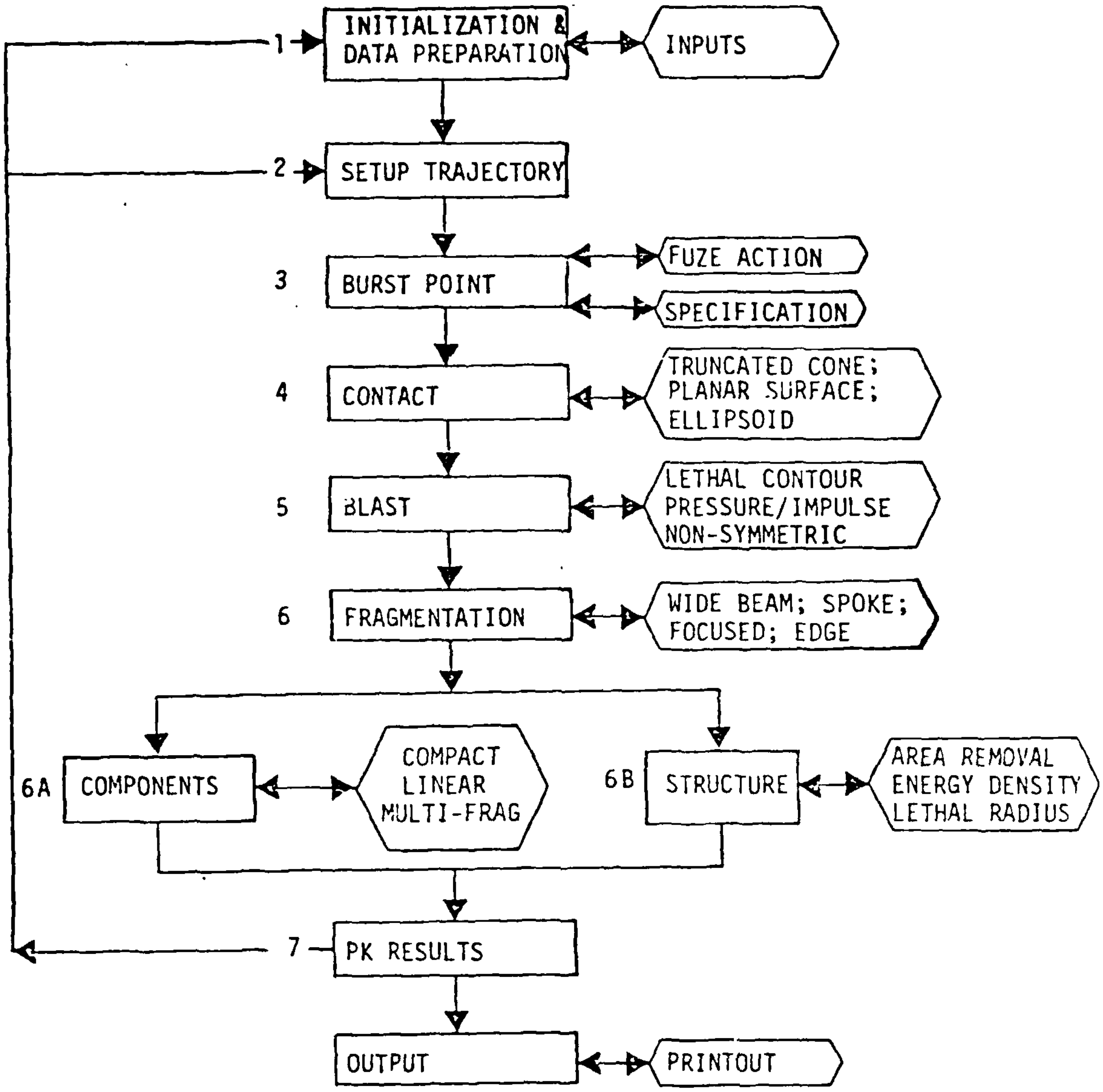


Figure 5. REFMOD Main Structure

3.3 KILL LEVELS

To assess the vulnerability of both fixed-wing (F/W) and rotary-wing (R/W) aircraft in flight, four kill categories have been defined and adapted by a special panel. This panel is called the Vulnerability Assessment Quantification Panel of the Aerial Target Vulnerability Sub-Group for the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) Target Vulnerability Group. These kill categories; attrition, forced landing, mission, and mission available; are defined along with the different levels of kill within each category, where applicable [11].

<u>Attrition</u>

This category covers those aircraft with combat damage so extensive that it is neither reasonable nor economical to repair. The attrition category is divided into six levels of kill. The first four are sequentially inclusive (i.e., "B" includes "A," "K," and "KK;" "A" includes "K" and "KK;" and "K includes "KK") and time dependent. These kill levels are:

- "KK" Kill (also referred to as "catastrophic") - Level of kill associated with damage that will cause the aircraft to disintegrate immediately upon being hit. Damage to the structures of either F/W or R/W aircraft could result in "KK" kill. Structural disintegration is usually caused by blast from internally or externally detonated projectiles or missile warheads, fuel tank explosions, high aerial density fragment impacts from focussed blast fragment missile warheads, blast and fragmentation from engine blow-up or detonation of stored ordnance.

- "K" Kill - Level of kill associated with damage that will cause an aircraft to fall out of manned control within 30 seconds after being hit. Damage to the following components could result in "K" kill:

  F/W - Pilot (single), structure, engine (single), flight controls, ammunition.

  R/W - Pilot (single), structure, main rotor group, ammunition.

- "A" Kill - Level of kill associated with damage that will cause an aircraft to fall out of manned control within five minutes after being hit. Damage to the following components could result in "A" kill:

F/W - Engine, fuel, controls (mechanical and/or hydraulic).

R/W - Engine, fuel, controls (mechanical and/or hydraulic).

- "B" Kill - Level of kill associated with damage that will cause an aircraft to fall out of manned control within 30 minutes after being hit. Damage to the following components could result in "B" kill:

  F/W - Same as for "A" kill plus other engine and fuel system components.

  R/W - Same as for "A" kill plus other engine and fuel system components.

- "C" Kill - Level of kill associated with damage that will cause an aircraft to fall out of manned control before completing its mission.

- "E" Kill - Level of kill associated with damage that will cause an aircraft to sustain additional levels of damage upon landing and makes it uneconomical to repair as specified by the applicable Technical Orders (TO's), Technical Bulletins (TB's), and regulations. Damage to the landing gear, controls, or control surfaces of aircraft could result in "E" kill.

Forced Landing

This category covers those aircraft with combat damage that forces the crew to execute a controlled landing (powered or unpowered). This category includes aircraft with damage which will require repairs for flight to another area and aircraft with damage which cannot be repaired on-site but which can be recovered by a special team. Damage to the following components could result in forced landing:

F/W - Hydraulics, fuel lines, electrical system, engine.

R/W - Engines (single), main transmission lubrication, tail rotor drive (includes gearboxes), tail rotor control systems

Mission (Mission Abort)

This category covers any aircraft with combat damage that prevents the aircraft from completing the designated mission but permits it to return to base.

Mission Available

This category covers those aircraft that have landed with combat damage and will require repair before returning to mission-ready status. There are different levels (intervals) of mission availability which are expressed as MA_X. The subscript X is the interval of time required to accomplish repairs. This interval is expressed in elapsed time, total manhours, or combinations thereof. In this category, one assumes that the necessary personnel, equipment, and supplies are available.

Some of the U.S. kill level definitions for fixed-wing aircraft are illustrated in Figure 6. The attrition kills which are sequentially inclusive (KK, K, A, and B) are wholly within the attrition circle. These circle diameters have a time correlation of immediate (practically taken to be one second), 30 seconds, five minutes, and 30 minutes for the aircraft to fall out of control after being hit. These circle diameters are not directly proportional to these times, but are related thereto. The circle diameters are more a function of the number of components subject to damage, the exposure, the "hardness" of these components, and the sensitivity of the aircraft to the malfunction of the components/systems, than only to the time required for the damaged component or system to cease to function.

According to the definition of the category Mission Abort, this is the part of the mission kill circle in Figure 6 which is not included in the attrition circle. C-kill is only a part of the intersection of the attrition and mission kill circles as this intersection can contain such cases as not being able to deliver weapons, and aircraft lost on return to the landing field.

For U.S. evaluation of rotary-wing aircraft (see Figure 7), the attrition category can be roughly equated to the A-kill category, the mission abort category with the mission kill less the attrition.

3.4 TARGET DESCRIPTION AND VULNERABLE AREA TECHNIQUES

The shotline generation program is written to use the combinational geometry, (GIFT, MAGIC) or the triangular approximation (SHOTGEN, POINT BURST GEN) technique, or both (FASTGEN). These target description techniques are sufficiently dissimilar that very few target descriptions prepared using one technique can be used in a program which uses another technique.

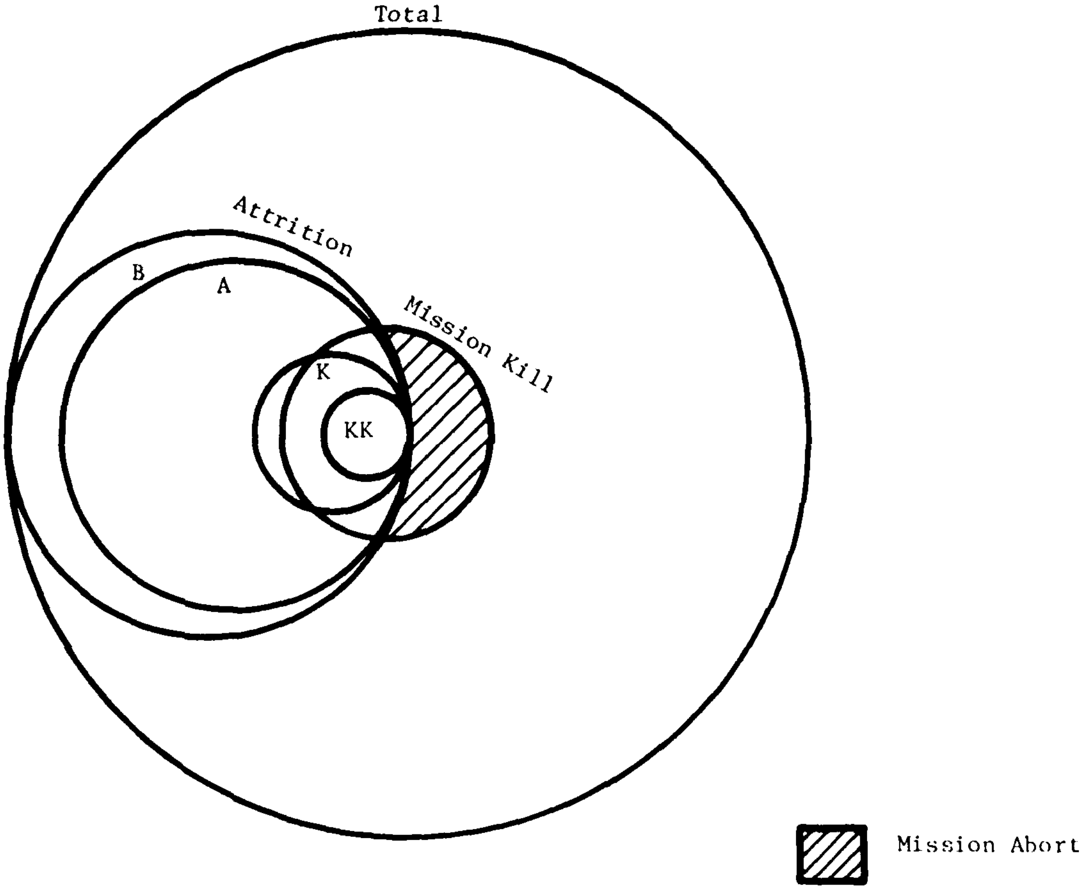


Figure 6. Venn Diagram of U.S. Kill Level Definitions for Fixed-Wing Aircraft

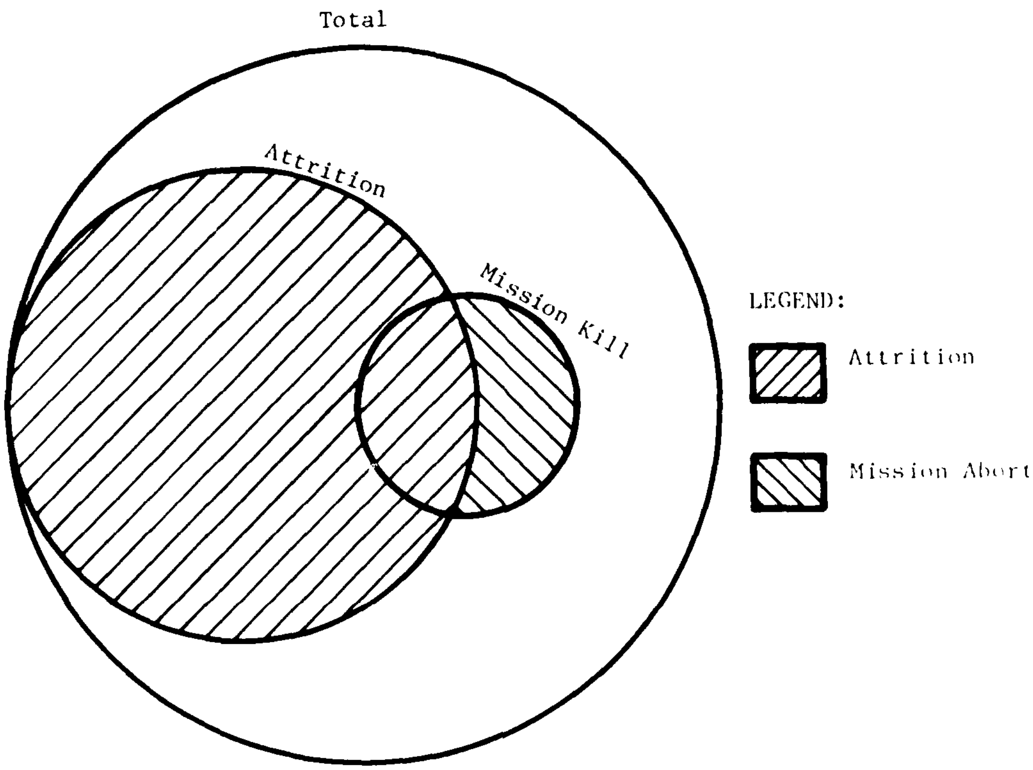


Figure 7. Venn Diagram of U.S. Kill Level Definitions for Rotary Wing-Aircraft

Therefore, in the U.S. there are several types of "target descriptions" for use with aerial targets, which must be matched to specific shotline generation programs for use. Also, different organizations in the U.S. are not equally able to use the different shotline generation programs. A brief description of SHOTGEN and COVART is given here and a section of the FASTGEN documentation is given in Appendix A.

Vulnerability programs require a target description input detailed and complete enough to represent the target ballistically from the attack aspect(s) considered. The Shot Generator Computer Program provides a detailed target description by developing detailed item-by-item listings of the components and air spaces encountered by a large number of uniformly distributed parallel rays emanating from any attack aspect and passing through any type of target.

The method used to obtain the basic input data for the description of any target is based on the fact that the surfaces, flat or curved, exterior or interior, of the individual components of that target can be approximated by a group of flat surface segments and therefore can be described as a series of consecutively adjacent triangles whose points (vertices) can then be located in space.

The computer routine transforms the target triangle points relative to the attack aspect being considered and superimposes a grid over the surface of the target as viewed from the attach aspect. Any grid size can be specified. Parallel rays are randomly located in each grid cell and the routine checks for ray encounters with component surfaces as it passes through the target. Each ray-surface encounter is listed sequentially and identifies the ray location, the component identification, the surface thickness, entrance and exit obliquity angles, the air spaces encountered, and the distance between the components.

Basic input data consist of:

- The coordinate measurements from a given origin in space.
- The code number, which is composed of the plate mode or influence mode symbol (when applicable), a normal thickness (when applicable), a space identification code number, and a component identification code number.
- The sequence number.

These data are required for each and every target point of the complete target.

The COVART computer program (see Figure 8) provides a method for determining the vulnerable areas and estimated repair times associated with specific levels of damage which are caused by single penetrators for various target types. The primary emphasis of this model is given to aerial targets; however, this program can also be applied to the problem of determining vulnerable areas of ground targets which are consistent with the traditional damage definitions for these targets.

The COVART program requires, as input, information generated by tracing shot lines through a geometric description of the target. Therefore, the COVART program has been written to accept shot line information which has been generated by the SHOTGEN or the MAGIC computer program, or equivalent; however, the dependence on these programs is not vital. The shot line input is independent of the source, provided the input format restrictions are met. The shot lines for a given aspect of approach to the target are parallel lines and simulate potential trajectories through the target for nonexploding penetrators. The penetrators are assumed to have been fired from a source distant enough that their trajectories are essentially parallel in the vicinity of the target.

Vulnerable areas and repair effort (if desired) are determined for penetrators (fragments or projectiles) impacting on the target skin within a preselected weight and speed matrix. Each penetrator is evaluated along each shot line, and the contributions made along that trajectory to the target vulnerable area and repair effort are determined. The aircraft velocity can be included when projectiles are evaluated. The weight and speed reductions for the penetrator are computed upon encounter with the surfaces of the various resisting target structures. Whenever a critical component is struck by the penetrator, the probability of kill is interpolated from data in which the probability is expressed as a function of threat impact (weight and speed). The component defeat probabilities are then combined for the various damage definitions in order to produce the target defeat probabilities for the given threat.

3.5 CHARACTERIZATION OF WARHEADS

Figure 9 depicts the basic ways a warhead can be configured to distribute the fragments radiating outwards after detonation occurs. Fragment distributions A, B, and C are treated exclusively, while pattern D is a

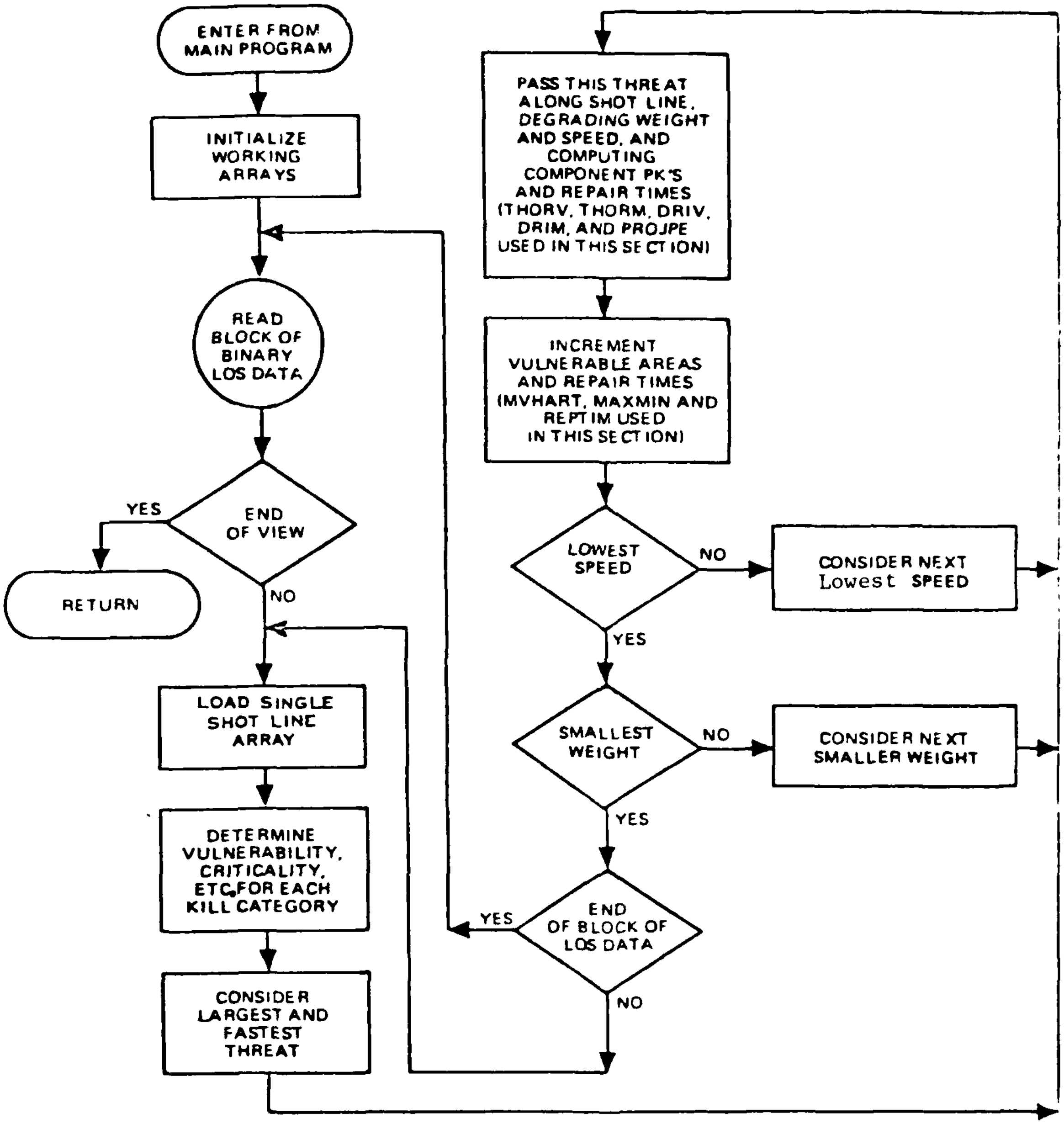
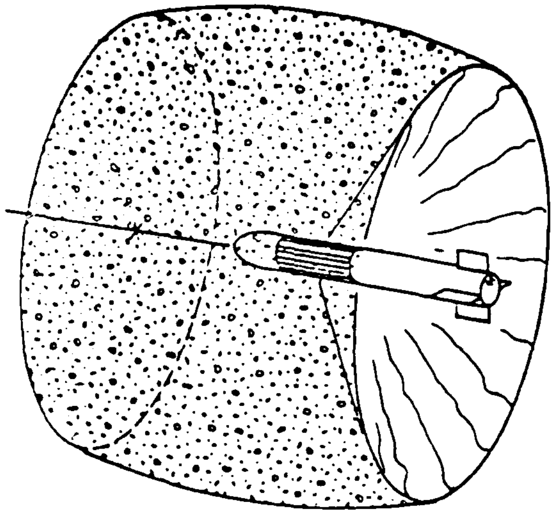
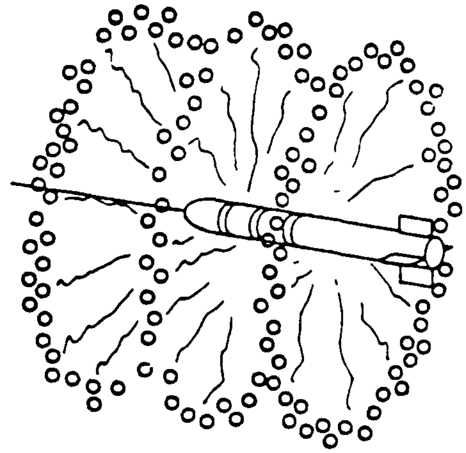


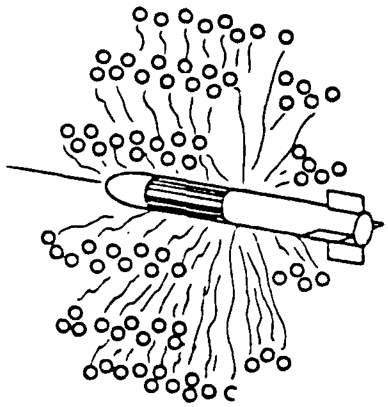
Figure 8. COVART Subroutine AREAS Conceptual Flowchart



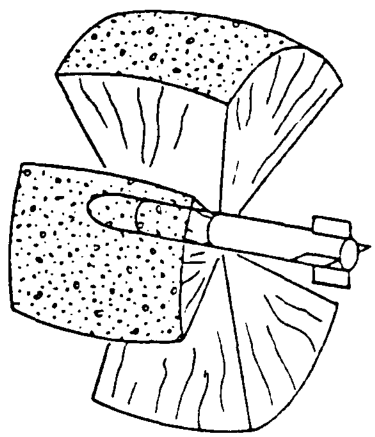
A. Distributed Fragments



B. Polar Zone Boundary Aligned Fragments



C. Radial Zone Boundary Aligned Fragments



D. Mapped Fragments

Figure 9. Warhead Types

specialization of A. The input variables describing the warhead allow great flexibility for specifying the fragment patterns ejected by a subject warhead:

- Polar zone angles and location of the polar zone cone apex on the warhead axis are specified by input.
- Boundary option -- fragments are located on the polar zone boundary. This option is used for continuous rod warheads and discontinuous rod warheads with expected value lethal radius vulnerability data.
- Zone option -- fragments are distributed within the polar zone. This option is used with vulnerable area and presented area expected value lethal radius vulnerability data.
- Radial zones are specified by input.
- Static fly-off velocities are specified for zone boundaries for each fragment class.
- Quantities of fragments of each class are specified for each polar and radial zone.
- Presented area and drag coefficient are specified for each fragment class.
- Zone boundary angles and fragment velocities are shifted by adding the components of missile velocity or relative velocity along the warhead axis and normal to the warhead axis. Zone boundaries are overlap or cross.

In Reference 14, Westine and Vargas review the two methods available for determining the fragmentation characteristics of a warhead experimentally (arena test data) and analytically (Mott and Gurney Equations).

3.6 TERMINAL EFFECTS

REFMOD uses the vulnerable area data to produce the kill probabilities. Vulnerable area tables (26 views) are interpolated using fragment striking azimuth, elevation, mass and velocity. A function of the total component vulnerable area is used proportional to the function of the component which is within the fragment zone. The components are described as linear or spherical. The expected number of lethal hits in each component are computed and the components are combined as singly-vulnerable components or multiply-vulnerable component sets. Some components also have a vulnerable area that is based upon multiplying effects and that is a function of fragment density.

REFMOD allows special treatment if either the warhead or target vulnerability is uniquely defined. Warheads falling in this category include continuous rod warheads, spoke warheads, and very narrow beam fragmentation warheads. Unique target vulnerability representation can include features such as a lethal radius, a critical number of fragments hitting a component, or any other multi-fragment, multi-component combination. The target elements are represented by cylinders or planes.

Once the intercept has been found, the radius from the warhead to target element and the fragment striking direction can be determined. If the kill probability depends only on lethal radius, no further computations are required. When a specified number of fragment hits are required to achieve a kill, the routine computes the expected number of hits using the polar zone density and the area of intersection of the polar zone and the cylinder. The expected number of hits is used in a Poisson series to compute the probability of achieving the critical number of hits or greater.

In the case of the spoke warhead, the computation involves first computing the probability of spoke intersection with the component and then the probability that at least the critical number of fragments will intersect the cylinder.

For fragments against structure, either the area removal criterion or the energy density threshold is used. In the first case, the structural members are identified by the coordinates of their end points and an associated presented area. In the energy criterion, the target elements are represented by cylinders.

The blast can be treated in different ways. A simple blast contour (volume) around the target can represent its vulnerability to a blast kill. If a warhead detonates within the volume, a blast kill is recorded. Another method that permits description of non-symmetric blast waves is to use existing target blast contours in conjunction with centers of blast damage as the target descrip ion. Warhead pressure and impulse are compared with critical values of these parameters.

REFMOD also determines whether the contact fuze function initiates rather than the proximity fuze function, resulting in a contact kill of the target. The missile is modeled as a series of points which, if they contact the target, will activate the fuze and result in a contact kill. The

target is modeled as a collection of either truncated elliptic cones, ellipsoids or planar surfaces for evaluation of the proximity fuze functioning.

The result from each run of the program is (for a given warhead detonating at a given burst point against a given aircraft) the probability of the kill category studied. If another kill category is desired, a new run must be made.

4.0 COMPARISON OF METHODOLOGIES

4.1 COVERAGE

The three U.S. computer programs described here cover somewhat more than the Swedish programs. Fuzes are not modeled in LMP-3, but are treated in other programs (different programs for different kinds of fuzes) in Sweden. A very brief description of what is treated in each program in the U.S. and Sweden is shown in Figure 1. The same kinds of problems are treated, but the limits between the programs are a little different. Many of the problems are also solved with the same assumptions and equations, but for some of them, there are differences. One great difference is the treament of the fragments' capability to penetrate the target.

The fragment penetration calculation is made in great detail in COVART. For every new target that is studied and for every fragment size and velocity, this calculation is made over again. However, the calculation is only made for fragments hitting the target from certain directions. When other directions are needed, the values of these are interpolated from those calculated. REFMOD uses data from COVART for 26 views, if available.

In Sweden, the fragment penetration calculation is only made in a detailed manner once. A computer program is used and the calculations are made for one size of fragment against one aircraft for all directions. The results are then used to give the parameters of a distribution function that will give the probability of any kind of fragment to reach a component inside any aircraft. This method is very time-saving but the accuracy may be questioned since these functions are extrapolated far from their original test data base.

When considering the precision of a method there is, however, always a question of the need for that precision. In both countires, the survivability and vulnerability studies are dependent upon the detail of the aircraft description. It is also true that different types of studies require targets modeled with more or less detail. Since much effort must be expended to make a target description, an existing description is used in all types of studies. We are not aware of the existence of both a high and a low detail description of the same aircraft in either country.

Many studies also have to be completed in a short time, so there is no time to describe a new target. One has to choose a target that is

already described even if it is not exactly what is desirable. In both countries there seems to be a nned for accurate methods of moderate precision which can be used in lieu of the ordinary, more time-consuming method.

The manhours needed to make a target description are said to be approximately the same for both methods. However, no comparison was made in this program.

The experimental and analytical methods used to obtain the fragmentation characteristics seem to be similar. In Janzon [15 and 16], a comparison is made between the analytical methodologies and the agreement is good up to 20 cm caliber which is the upper limit of the Swedish equations.

Calculations of whether or not the components are hit by fragments and methodologies for converting damage of components into a kill probability for the target uses the same equations and assumptions in both models. However, the definition and use of damage criteria make the U.S. model more component-orientated and the Swedish model more system-oriented. Component kill, depending on fragment size and velocity, is treated in more detail in the U.S. while malfunctioning of the systems, combining effects on aircraft and pilot's behavior, is treated more comprehensively in Sweden. A review of different computer programs and their input data, which are used in each country to calculate fragments' effect, is shown in Figure 10.

The blast effect is treated in almost the same way. At least the possibility is there, but the gaps in experimental information are more serious in Sweden than in the U.S. Overall, much more experimental data are available in the U.S. than in Sweden. The gaps will, however, always exist since obtaining experimental data is time consuming and expensive. For that reason, assumptions leading to simple equations are desirable.

Structural members are not treated as critical in the LMP-3 models in the manner in which they are in REFMOD. In LMP-3 the structure is only described as a weight causing retardation of fragments. No matter how many fragments hit, no increase in target kill probability is recorded in LMP-3.

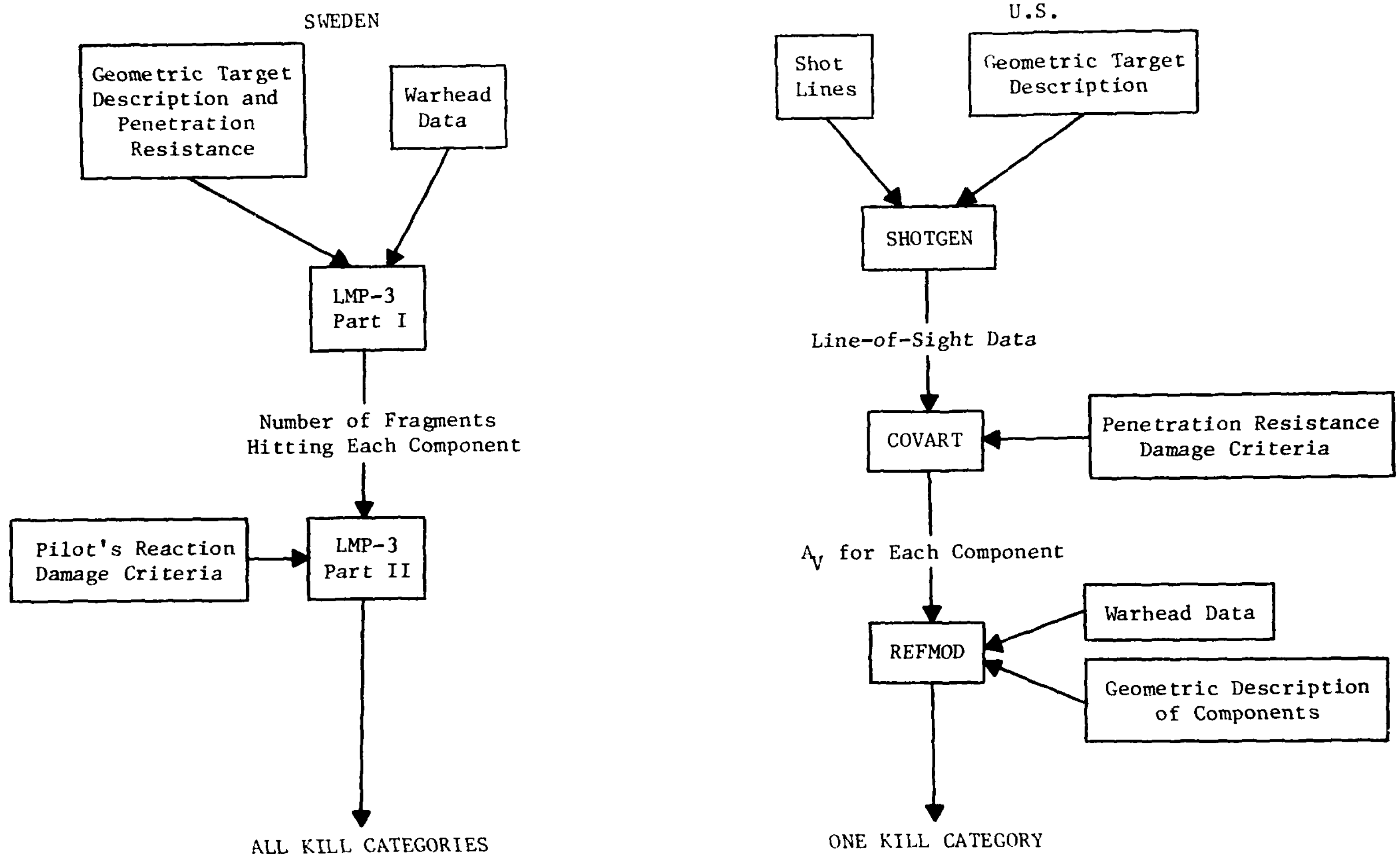


Figure 10. Fragment Effect Calculations in Sweden and the U.S.

Aircraft fuel fire problems have received a great deal of attention in the U. S. The complexity of the physical processes involved has forced computer simulators to treat only a few factors explicitly. The COVART computer model treats six parameters: fuel type, cell wall type, threat type, threat speed, distance from flash origin to contact with fuel (air gap), and the presence of intervening surfaces. The LMP-3 model treats fire as part of the probability of occurrence of Events 1 or 3 when the fuel cell is hit by fragments. This probability can be increased or decreased depending on the construction of the cell, the threat, or the fuel type, but no calculations are made to give the conditions at impact such as temperature, air gap, pressure, or leakage onto hot aircraft surfaces.

Neither in the U.S. nor in Sweden has the sensitivity of the vulnerability studies to the assumptions, approximations and data inputs been determined. Some sensitivity studies are completed; none were extensive investigations to guide the development of data bases and refinements or simplifications of the computer methodology for aircraft vulnerability assessment.

4.2 COMPARISON OF FRAGMENT PENETRATION

4.2.1 Fragment Penetration in LMP-3

LMP-3 uses a set of "fragment retardation functions" to predict the probability that a fragment will penetrate a sufficient depth, x, within a specific volume of the aircraft with an adequate momentum per unit area, I, to incapacitate a given component. This incapacitating momentum per unit area, Y, which the fragment must possess is that which is necessary to perforate the aircraft skin, to travel to the component, and to incapacitate the component. Each line segment, representing all or part of a critical component, is located within a volume of the aircraft (represented by a polyhedron) which is assumed to have a skin and a homogenous density. These fragment retardation functions were developed in a study in which the J 35 Draken was described in detail (10,000 components). This study consisted of tracing a multitude of fragment trajectories to determine fragment momentum per unit area as the 7.8 gram steel cubes perforated the skin, then traversed a specific polyhedron to a given component.

Assuming that the capability of the target to retard the fragment is determined by the skin and the internal density, the expected or mean value of the momentum per unit area, Y, is a linear function of the depth of penetration, x, or $E(Y) = a + b_x$. (1)

The intercept a on the Y axis is a proportional to the skin thickness t (mm aluminum), and the slope, b, is proportional to the internal density, ρ. In the aforementioned study, empirically determined coefficients were obtained such that $a = C_1 . t$ and $b = C_2 . \rho$ for the fuselage, and that $b = C_3 . \rho$ for the wings. The internal density ρ for a polyhedron is calculated as:

$$\rho = \frac{\text{total mass - mass of the skin}}{\text{volume}} \tag{2}$$

and the thickness t if the material is not aluminum

$$t = \frac{\text{thickness of place x density plate}}{\text{density of aluminum}} \tag{3}$$

Penetration into aluminum was predicted using

$$x = \theta \frac{m_f \cdot ^{V}}{A_f} \tag{4}$$

where: x = thickness which the fragment will just perforate

θ = an empirically derived constant depending on material of fragment and plate and also shape of fragment (this constant has dimensions of reciprocals of the density and reciprocal of velocity of sound)

m_f = mass of fragment

V = striking velocity

A_f = cross-sectional area of the fragment.

Test data were used to determine the valuesof θ [17].

As the study was made using only steel cubes, corrections are necessary if the fragment retardation functions are to be valid for other types of fragments. When other material fragments are used, their mass is changed to the mass of a steel cube with the same capability of perforation as the steel fragment. This means that instead of the actual mass m_A of a

fragment, the mass m_c is used in LMP-3. The term m_c is given by the following equation:

$$m_c = \frac{\theta \text{ (fragment A)}}{\theta \text{ (steel cube)}} \cdot m_A . \tag{5}$$

Note that there is a relationship of mass per presented area used to relate relative presentation capabilities of fragments of different materials.

The momentum per impacted area (Y) was calculated and the results were processed statistically and presented in diagram form for various penetration intervals in various parts of the aircraft. The parameter, ℓ_n Y, is assumed to be a normally distributed function (N) whose mean value is m and whose standard deviation is σ, or

$$\ell n \ Y \sim N \ (m,\sigma). \tag{6}$$

By definition, m is the expected value of ℓn Y, or

$$m = E \ (\ell n \ Y). \tag{7}$$

Also one may determine that

$$E(Y) = e^{m + \sigma^2/2} \tag{8}$$

of $$m = \ell n E(Y) - \frac{\sigma^2}{2} \tag{8a}$$

where $E(Y) = a + bx.$

In the original calculation of the fragment-retarding function, we had assumed $\ell n \ Y \sim N(m,\sigma)$. The standard deviation, σ, was found to be independent of the depth of penetration, but va ed with the internal density ρ. In approximating m by means of a straight line (we have assumed that E (Y) = a + bx and that b $\approx$ ρ), therefore, σ should be a function of ℓn ρ, and, for the

Fuselage: $\sigma = C_4 + C_5 \cdot \ \ell_n \ \rho,$

while for the Wing: $\sigma = C_6 + C_5 \cdot \ln \rho$

where C_1, C_2, C_3, C_4, C_5, C_6 are empirically derived constants.

The probability, p, for a fragment to reach a component a distance, x, within the aircraft is the probability P that the capability, Y, of the target to retard the fragment within that distance is less than the momentum per unit area, I, which the fragment possesses at impact

$$p = P(Y < I) = \phi \; \frac{\ln I - m(x)}{\sigma(x)} \tag{9}$$

This provides an easily computed fragment penetration criterion for any fragmenting warhead against any aircraft for which the retardation capability is given only by skin thickness and local aircraft density.

4.2.2 Fragment Penetration in COVART

Program COVART uses the penetration equations recommended by the Penetration Equations Panel of the Aerial Targets Vulnerability Subgroup in August, 1972 [5]. The theory used for penetration of a target is that a penetrator travels along a shot line through the target, it encounters resistance offered by solid and liquid components of the target. Under certain circumstances, those encounters result in a reduction in the weight and speed of the penetrator. The magnitude of the reduction of each of these quantities is a function of:

- Weight, speed, and shape of penetrator at impact,
- Impact obliquity,
- Material of component, and
- Thickness of component [18].

The COVART computer program deals with fragment and projectile penetrators and their interaction with solid and liquid resisting media. The residual speed and weight for the penetrator is determined after each perforation of a resisting medium.

Fragments produced from large caliber artillery weapons are presumed to be compact, irregular in shape, and weighing up to 240 grains. Impact speeds up to 10,000 feet per second should be considered. The techniques outlined in NWC TP 4871, "Transformation of Terminal Ballistic Threat Definitions into Vital Component Malfuction Predictions" seem appropriate to predictions involving these fragments. Specifically, the algorithm of the above report, applied to irregular fragments impacting aluminum target sheets, is used in COVART [5]. The algorithm is appropriate to a wide variety of possible impact conditions; however, only aircraft targets are discussed. According to the algorithm, the THOR equations are the bases for calculations. This is especially true where naturally fragmenting warheads are considered, and where aluminum target sheets are impacted by corners of fragments. COVART uses the following procedures quoted from Reference 5:

"(1) For fragment impacts on aluminum target sheets, the THOR residual weight loss equation should be used. For simplicity, the THOR residual weight loss equation for steel should also be used because the frequency and thickness of steel materials encountered in aircraft targets are small.

(2) For impacts on titanium sheets, the THOR residual weight loss equation should be used subject to the condition that the correlation parameter from steel deformation weight loss model be greater than 1,000; otherwise, the residual weight of fragments perforating titanium should be assumed to be equal to the impacting weight (NWC TP 4871, page 107).

(3) For other materials (e.g., magnesium, glass fiber laminate, plexiglass, etc.), THOR predictive weight loss equations should be used. If necessary, equivalent thicknesses of aluminum should be based upon equal areal densitites.

(4) Residual fragment speed predictions after perforations of all metallic target materials should be based upon the DRI penetration equation. This equation provides good agreement with test results for the fragment sizes and speed ranges being assessed, and incorporates the finding of both the DRI and THOR studies. The equation recommended in NWC TP 4871 is:

$$V_r = \frac{\sqrt{V^2 - V_{50}^2}}{1 + M_s/M_p} \tag{10}$$

where V_r = residual penetrator speed, ft/sec

V = penetrator impact speed, ft/sec

$$M_s/M_p = \frac{\rho_s A_p T_s}{M_p \cos\theta} \text{ or } M_s/M_p = \frac{\rho_s T_s}{\rho_p L_p \cos\theta}$$

with ρ_s = specific weight of plate material, grains/in3

A_p = presented area of penetrator, in^2

T_s = normal thickness of plate material at impact point, in.

M_p = weight of penetrator, grains

M_s = weight of target plug ejected during perforation at any impact obliquity, θ, grains

θ = striking obliquity angle

ρ_p = specified weight of penetrator, grains/in^3

L_p = length of penetrator, in.

and V_{50} = ballistic limit velocity, ft/sec

where $$V_{50} = 10^{C_1} T_s^{\alpha_1} M_p^{\beta_1} \sec\theta \tag{11}$$

and C_1, α_1, and β_1 are THOR constants defined in THOR 47 and 51.

Residual fragment speeds through liquids should be based upon direct fluid drag equations as given in BRL MR 488, "Report on First Working Conference on Aircraft Vulnerability," March 1949. For fragments and projectiles, these equations reduce to

$$V_r = V \exp(-C_D A_p \rho_s D/2M_p) \qquad (12)$$

where C_D = 0.6 for projectiles and 0.75 for fragments
ρ_s = fluid density, grains/in^3
D = distance, in.

These procedures apply only to those target vulnerability assessments being performed for the JTCG/ME Aerial Target Vulnerability Subgroup. They may be updated for future use upon additional test firing programs and data analyses.

Current JTCG/ME recommended procedures for handling projectile penetration are presented as follows:

(1) For 14.5 mm and larger API ammunition impacting on the first component (aluminum or steel):

(a) Compute the presented area of the impacting projectile from the encounter conditions and velocity vectors.

(b) Determine if the projectile incendiary component functions by reference to the criteria listed in NADC Report 72039-5D.*

(c) If the incendiary component does not function, assume that the projectile residual speed and weight remain unchanged after penetration of the first target.

* Also in the JTCG/ME Penetration Handbook.

(d) If the incendiary component functions, select the residual projectile weight, and compute residual speed from THOR TR 66 or TR 77, as applicable.

(e) The Classified Addendum to the COVART documentation contains the necessary threat parameters for the penetration equations used in COVART, i.e., projectile critical core weights.*

(2) For 14.5 mm and larger API ammunition impacts on the second and subsequent components:

(a) Determine if the projectile incendiary component functions by reference to NADC Report 72039-5D. Repeat this step as required.

(b) If the incendiary component functioned on the first or subsequent target surfaces, compute the projected area of the projectile based upon the critical core weight (contained in the Classified Addendum which lists all necessary projectile threat parameters).

(c) Compute the residual speed of the projectile core from THOR TR 66 of TR 70, as applicable. Repeat this step as required.

(d) Maintain the residual projectile weight equal to the critical weight (contained in Classified Addendum in JTCG Penetration Handbook) for all subsequent impacts.

(3) For caliber 0.30 and caliber 0.50 API ammumition impacts on the first component:

(a) Compute the presented area of the impacting projectile from the encounter conditions and velocity vectors.

---

* These are also given for projectiles up to 37 mm in the JTCG/ME Penetration Handbook which is unclassified.

(b) Compute the projectile residual speed and weight from THOR TR 66 or TR 70, as applicable.

(4) For caliber 0.30 and caliber 0.50 API ammunition impacts on the second and subsequent components:

(a) If the weight of the projectile impacting the second or subsequent sheets is greater than the critical weight, compute the average presented area of this projectile based upon a cylinder of cross-section diameter equal to the core diameter, and length determined from weight.

(b) For this projectile, compute residual weights and speeds based upon THOR TR 66 of TR 70, as applicable.

(c) If the weight of the projectile impacting the second or subsequent sheets is less than or equal to the critical weight, compute the average presented area of this projectile based upon a cylinder of cross-section diameter equal to the core diameter, and length determined from the weight.

(d) Maintain this same core weight for all subsequent target impacts.

(e) Compute residual projectile speeds from THOR TR 47.

(f) For impacts on target materials other than aluminum or steel, use equivalent thicknesses of aluminum or steel based upon equal areal densities.

Note: Fragment impacts on steel target sheets are treated as outlined in the algorithm reported in (NWC TP 4871, [5] pages 41-45)" [5].

4.2.3 Comparison of Fragment Penetration Equations Used in U.S. and Sweden

As the calculations of fragment penetration in LMP-3 are quite different than those used in COVART, direct comparison of the two methodologies

is not possible. However, the equations based on experimental data can be compared.

The swedish penetration equation calculates the ballistic limit V_{BL}, the velocity the fragment needs just to perforate a plate. If the fragment has a higher velocity than V_{BL} and therefore will perforate the plate, the fragment velocity after the perforation is the striking velocity reduced by V_{BL}, and the mass of the fragment is not changed.

The equation is based on experimental data and is said to be valid for velocities up to 1500 m/s. However, the equation is used today for higher velocities in the vulnerability/survivability computer models. The equation is also limited to those kinds of fragments and target materials for which experimental data are available. Today, data are available for spherical, cubical and irregular fragments of aluminum, steel, or tungsten against steel, aluminum, or titanium.

The equations used in the U.S. calculate both the mass and velocity reduction of the fragment when perforating a plate. The equations are based on experimental data of cylindrical steel fragments against both metals and non-metals. The experimental data cover velocities up to approximately 3000 m/s.

The results from the Swedish and the U.S. equations do not differ when calculating the fragments' capability to perforate one plate. The differences, however, are obvious when calculating the perforation of a second plate and for higher velocities. If the Swedish equation is extended for higher velocities, this means that the depth of perforation in a second plate will increase as the striking velocity increases as shown in Figure 11. This is not true since we know that the fragments start to break up. The velocity at which breakup occurs depends on the fragment and target materials, the shape of the fragment, and the thickness of the plate. The THOR residual mass equation handles this problem to some extent since the mass of the fragment decreases as the velocity increases. However, the equation sometimes gives the residual mass equal to zero and even below zero, which means there is no effect on the second plate. In general, one can say that the equations give results as shown in Figure 11. This could well indicate that, for high striking velocities, one should expect

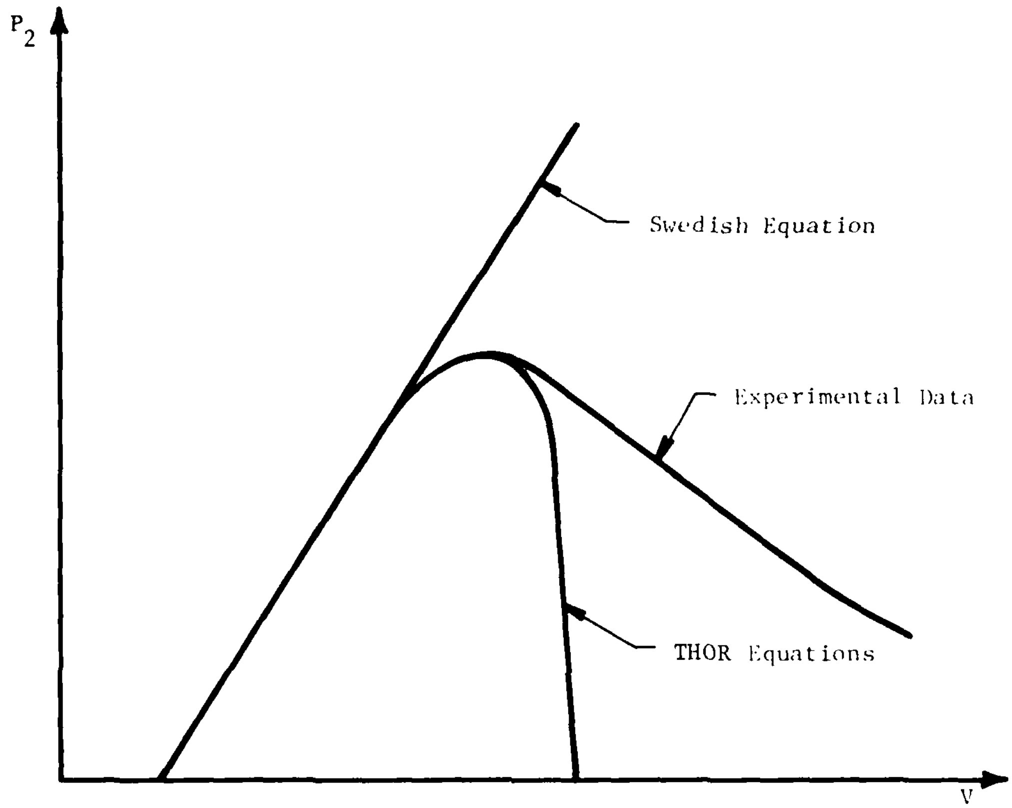


Figure 11. Depth of Penetration in the Second Plate as a Function of the Striking Velocity Against the First Plate, Steel Against Aluminum

Swedish vulnerability assessments to give a greater vulnerability than would U.S. vulnerability assessments, while the actual vulnerability is somewhere between the two, expecially where fragment impacts are the principal damage mechanism.

4.3 COMPARISON OF CALCULATED NUMBER OF LETHAL FRAGMENT HITS ON A COMPONENT

4.3.1 Number of Lethal Fragment Hits on a Component in LMP-3

The critical components involved in the target's functional systems are described graphically by representing each component in the target's coordinate system by one or more line segments oriented in the target's longitudinal direction (parallel to the X axis, the aircraft centerline). Each component is ascribed a ballistic resistance, which is a measure of the residual momentum which a fragment must have in order to damage the component in question. Each component is also ascribed an area, which is the average of the areas of the real component in different directions, if the whole component is vulnerable to the fragments in question. This means that this characteristic presented area as used in the model does not change with attack aspect. If only 50 percent of the component is vulnerable, then this area is also 50 percent of the whole area. The components are grouped together in subsystems and the kill probability of the subsystem is dependent on the total number of fragments hitting the subsystem. In other words, there is no calculation of kill probability of each component but only the number of hits which then are added to the sum of hits on the subsystem.

To determine whether the component will be hit by fragments, the following calculations are made:

- Intersections between the line containing the line segment and the cones describing the boundaries of fragment zones are determined.
- The times for the fragments to reach those intersections with regard to the retardation in the air are calculated. The fragments are assumed to move along a straight line.
- The times for the line segment to reach those intersections are calculated. The times (and positions) at which the end points of the line segment will be reached by fragments can then easily

be interpolated. If the line segment is located in two or more fragment zones, it is divided into several subsegments, which are then treated separately. The area of the segment is also divided proportionally to the length of the subsegment.

- The density of fragments at the moment of impact is calculated as the total number of fragments within the zone divided by the surface over which they are supposed to be spread evenly. This surface is approximated by the surface of a frustum of a cone.
- The number of fragments hitting the line segment is the density of fragment times the area of the line segment (or subsegment).
- The area is increased by a factor which is a function of the cross-sectional area of the fragment.
- The expected number of lethal hits is estimated by the number of fragments hitting the component area represented by the line segment times the probability of those fragments reaching the line segment.

4.3.2 Number of Lethal Fragment Hits on a Component in REFMOD

There are four ways to represent a component in *REFMOD:* *a cylinder*, a plane, a line and a sphere. Only the last two are used when the vulnerable area of the component is known. For the cylinder, only a sector of the surface can be vulnerable and it is determined when that sector is visible to warhead fragments and struck by them.

The intersection of the fragment zone boundaries with the component is computed using an iteration process which considers fragment drag based on a constant drag coefficient.

At the warhead's detonation point, a specified fragment class has the following information from input:

- Static polar boundaries
- Static radial boundaries
- Static ejection velocity at polar zone boundaries

The zone boundaries and ejection velocities are altered by the vector addition of the missile/target relative velocity vector to account for the dynamics of the terminal encounter.

During the time that a fragment travels from its position at detonation to its intercept with a point on the target, the target will move from its original point to an intercept point. The intercept position computation is performed by solving a set of transcendental equations which are a function of:

- Fragment mass
- Fragment shape
- Fragment ejection velocity
- Drag coefficient
- Initial position of target with respect to detonating warhead
- Distance fragment travels prior to impacting target

These equations are solved by iteration. The alteration of the zone boundaries and fragment velocities are a part of that iteration process in which the average fragment velocity from the warhead position at detonation to the zone boundary intercept with a point on the target is determined. A solution is assumed when the average fragment velocity determined between the successive iterations is within 100 feet per second.

The intercept of the polar zone boundaries with the component is determined using vector algebra and the following variables:

- Average fragment velocity
- Dynamic polar zone boundaries
- Missile, target, and relative velocity vectors
- Vector position of component

Once the intercept position is known, the fragment impact velocity, direction, and beam area can be obtained. The fragment beam area is the area on a spherical surface within the radial zone at the distance from the warhead to the intercept point with the target point.

If the component lethality is given by vulnerable area tables, those tables (26 views) are interpolated using fragment striking azimuth, elevation, mass, and velocity. The vulnerable areas of components with small

diameters and large length-to-diameter ratios are corrected to account for grazing near-misses. The fraction of the line or sphere diameter lying within the polar zone is used to modify the total vulnerable area of the component. If a given fragment class has encountered the target component, its vulnerable area within the fragment beam is projected into the fragment beam area. Fragment density is the number of fragments in the given polar and radial zone divided by the fragment beam area. The expected number of lethal hits is estimated by the fragment density times the vulnerable area.

4.3.3 Comparison of Methods of Calculating the Number of Lethal Fragment Hits on a Component

In both models, the fragment flight path has been assumed to be so short that gravity can be ignored, and it is only necessary to use one drag coefficient in the flight path calculations.

The drag coefficients used are almost the same in both countries. The coefficients are a function of the Mach number but that is not included in the models. However, as can be seen in Figure 12, the curve fittings to the experimental data are almost the same in both countries.

The calculations that are made to find the point of intersection between the fragments and the target are different. In REFMOD, an iterative technique is used to simulate the motion of a fragment along its trajectory relative to the target. In LMP-3, the times for the fragments and for the components to reach certain points are calculated and the time when the fragments will reach the components is then interpolated from those times. The results will probably not differ much.

To determine whether a component or a fraction of one is within the boundaries of a fragment zone, similar approximations are made. If a fraction of a component is within the boundaries, the area of the component is proportioned to the fraction of the cylinder axis or sphere diameter in REFMOD and in LMP-3, to the fraction of the line segment.

Corrections for near misses are made in both programs. In LMP-3, corrections are made for all components and in COVART only for those with large length-to-diameter ratios.

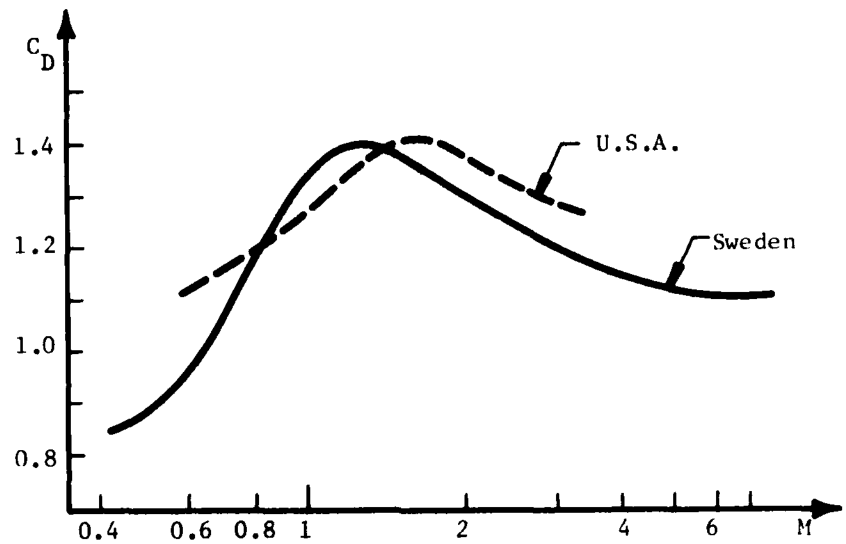


Figure 12. Drag Coefficient as a Function of Mach Number for Shell Fragments

To determine the density of fragments, the same assumption is made that the fragments are evenly spread over an area. In LMP-3, this area is approximated by the surface of a frustum. This surface is too small since the fragment front is convex. The spherical surface which is used in REFMOD is more correct.

The number of lethal hits is calculated in the same way except that the fragment capability to reach the component is in the parameter vulnerable area in REFMOD and is calculated separately as a probability in LMP-3.

Changes in attack aspect are best treated in REFMOD where interpolations in the vulnerable area tables are made between predetermined views. The characteristic area of a component does not change with the attack aspect in LMP-3, but only the probability for a fragment to reach the component, because the distance the fragment has to penetrate changes.

4.4 COMPARISON OF FRAGMENT STRUCTURAL KILL

4.4.1 Fragment Structural Kill in LMP-3

LMP-3 does not treat structural kill. The structure is only considered as retarding the fragments and is not considered critical.

4.4.2 Fragment Structural Kill in REFMOD

Two criteria to kill the structure are used in REFMOD. These are area removal, and energy and mass density threshold values.

The area removal methodology is that used in the AMEGS computer program. Structure members are identified by the coordinates of their end points and an associated presented area. The criterion for killing structural members is a percentage (decimal fraction) of metal which must be removed to break the structural member. Given fragment velocity, size, presented area, and the failure criterion, the program calculates the number of hits on a member necessary to cause it to fail.

The dimensions of the member are found in terms of fragment sizes. Knowing the fragment zones from the warhead which intersects the member, the probability of failing the member is found analytically. The solution is based on the requirement that, given a hit at any point on the bottom row of the member, other effective hits considered occur at least one vertical cell and not more than one horizontal cell away.

The second model to compute a fragment structural kill mechanism uses energy and mass density threshold values.

The target elements are represented by cylinders. The intersections of the fragment zone boundaries with the surfaces of the cylinder representing the target element are computed using an iteration process which considers fragment drag based on a constant drag coefficient. The impact angle, fragment velocity, and fragment density (grains per square foot) are determined and used to compute energy density and mass density. If the energy density impacting the target element exceeds a specified threshold value, Pk is computed using a functional relationship based on energy density.

Each target cylinder is subdivided by a uniformly spaced set of segments for which the following information is input:

- Number of segments
- Minimum energy and mass density threshold for critical damage
- Striking angles for which the cylinder is vulnerable
- Values for the functional relationship defining Pk versus energy density

The warhead model and the intersection of the fragment polar zone boundaries with the target cylinder axis are analyzed using the same procedure described for the linear component model. If the fragment impact angle is acceptable, the cylinder segments within the fragment beam are identified. The impacting fragment energy density ($ft\text{-}lb/ft^2$) and mass density ($grains/ft^2$) are computed and stored in an array associated with the cylinder segments. All fragment zones and classes are examined and energy density and mass density are accumulated in the array for the segments. The value of the accumulated energy and mass density is examined and the kill probability is computed accordingly. If the accumulated energy density is sufficient to achieve a target kill ($P_k = 1.0$), the routine is exited and an energy density kill is scored.

4.4.3 Comparison of U.S. and Swedish Fragment Structural Kill

As there is no methodology to compute this in the Swedish model, there are no comparisons to be made. The question to be asked is rather: "Why are those calculations made in the U.S. model and not in the Swedish?" The Swedish methodology was developed to treat fragmenting warheads which are not designed to cause structural kills. The U.S. methodology was developed to treat warheads which are specifically designed to enhance the probability of obtaining structural kills. Therefore, to Sweden, a structural kill would be a result which would occur in an already fatally damaged aircraft; while in the U.S., a structural kill would be the principal result expected from certain warheads. The philosophy in Sweden has been that before enough fragments to destroy the structure have hit the target, there are so many components damaged that the target is already killed. So, if the damages of the components are determined there is no need for calculations of structural kill mechanisms. In the U.S. model, the structural kill calculations are made prior to the calculations of the components vulnerability and this methodology is effective when special or large warheads are treated.

4.5 COMPARISON OF CALCULATION OF BLAST EFFECTS

4.5.1 Calculations of Blast Effects in LMP-3

Contact fuzes are not treated in LMP-3 but in other computer programs which give the burst points as output. These internal burst points are then given as input data to LMP-3 and the effect calculations are completed there. The locations of the burst points are a function of the delay time of the fuze and the striking velocity of the round. The delay time is determined primarily from test firing and is given as a function of the angle of impact. The fuze activation can also be limited to certain values of this angle. The blast effect from these internal burst points is then treated in the following ways:

- Check if the burst point is within any predefined volume (component). If the burst point is within any of these volumes, blast damage is assumed. These volumes are described as boxes

or cylinders. The effect of contribution from blast in these components is added to the overall system effect as an additional subsystem and may contribute to Event 1, 2, or 3. The size of the volume does not depend on the size of the warhead. Examples of components which have been described as volumes are cabin or cockpit, inlet, fuel cells and engine.

- Check if any critical component is so close to the burst point that it will be damaged by the blast. At the detonation point, the warhead is surrounded by a truncated ellipsoid and as the components are described by line segments, the check requires only a calculation of intersections between lines and the ellipsoid. If a line segment is intersected, 1000 effective fragment impacts are added to that line segment which means that the component is totally damaged. The size of the ellipsoid depends on the size of the warhead and is given by the parameters defined in Figure 13. Examples of values used are:

  20 mm HEI   R = L = SL = 0.1 m

  40 mm HEI   R = L = SL = 0.2 m

- Reduce the capability of the structure to retard the fragments. Since the skin thickness is a parameter of the fragment retardation functions, the thickness in that part of the aircraft where the burst point is located is reduced by a factor. The value of this factor has been 0.5 or 0.9, depending on the warhead.

The blast effect from external burst points is treated in only one way and that is also by reducing the skin thickness. In this case, it is checked if the burst point is within a given distance from the target and if so, the reduction is made. A factor of 0.5 has been used and the distance has depended on the size of the warhead. As an example, a 40 mm HEI within 0.2 m from the skin reduces the thickness by 0.5.

4.5.2 Calculations of Blast Effect in REFMOD

The methodology used is essentially taken from the AMEGS model. There are two methods of evaluating blast kill. The first option allows

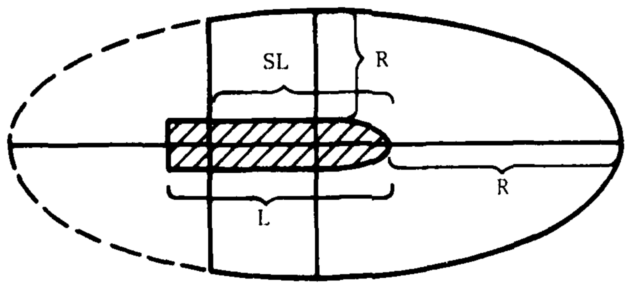


Figure 13. Blast Effect Around Warhead

the user to apply a simple blast contour (volume) around the target which represents its vulnerability to a blast kill. If a warhead detonates within the volume, a blast kill is recorded and P_k is set to 1.0; otherwise, P_k is set to 0.0. Note that the lethal blast volume includes altitude scaling. The lethal blast volume is described by ellipses appropriately sized and oriented. The coordinates of a burst point are substituted into the equation of the ellipse(s); if the result is less than 1, then the equation is satisfied and the burst point falls within the ellipse.

The second method of evaluating blast kill compares available warhead pressure and impulse with critical values of these parameters. If both are exceeded, blast kill is set to 1. One of the features of this method is that it permits description of non-symmetric blast waves. For a given warhead, pressure and impulse data are stored as a function of distance and angle off the longitudinal axis. The existing target blast contours are used in conjunction with centers of blast damage as the target description. The blast contours are used to establish the critical values of pressure and impulse. Since data for pressure and impulse are given at sea level, the critical values are scaled to target altitude. A critical radius is found for both pressure and impulse which is composed to the distance from burst point to pressure point. If both are smaller than the critical radii, a blast kill is recorded.

In REFMOD, it is determined whether contact fuzing occurs prior to proximity fuzing, resulting in a contact kill of the target.

The missile is modeled as a series of points which, if they contact the target will activate the fuze and result in a contact kill. These contact points as shown in Figure 14 are used to form rays which are parallel to the relative closing velocity. Calculations are made to determine whether any of the rays intersect the target which is represented by a set of truncated elliptic cones, ellipsoids or planar surfaces. The distance of intersection of the ray and the target is also computed and the intersection time is compared with the proximity fuze time to access contact kills. If a contact kill occurs, P_k is set to 1 and, if not, to 0.

4.5.3 Comparison of U.S. and Swedish Calculations of Blast Effect

For external burst points, there is no real treatment of the blast effect in the Swedish model, but only a higher probability of kill if the

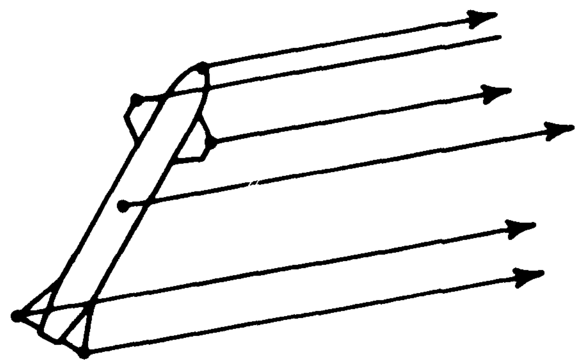


Figure 14. Contact Points of a Missile

detonation is close enough to the target. The fragment probability of reaching critical components will then increase as the skin thickness is reduced. This means that the blast only cannot kill the target, and if the burst point is so located and the warhead so shaped that no fragments will hit the target, no effect is recorded. The way the blast effect is treated in REFMOD gives a possibility of a more physically accurate solution of that problem. Overall, the blast effect from external burst points it better treated in REFMOD than in LMP-3 if test data are available and there are many more test data in the U.S. than in Sweden, especially concerning blast effects.

REFMOD is more oriented to treating contact fuzes for missiles than for HEI rounds. As it is the other way around in Swedish models, it is hard to compare the treatment of blast effects from internal burst points. In REFMOD the probability of kill is equal to 1 as soon as the contact fuze is activated. In LMP-3, calculations are made to determine the effect of both the blast and the fragment.

4.6 COMPARISON OF DAMAGE INTEGRATION MODEL

4.6.1 Damage Integration Model in LMP-3

The number (if any) of fragments hitting and damaging the component is determined for each component. The systems in which the components are combined are considered to be independent of one another, and are divided into two categories:

1. Systems which are rendered inoperable by one fragment (for example, cables, lines, pipes)
2. Systems for which the kill probability increases with the number of hits (for example, windshield, engine, tanks).

Each system represents a functional failure mode and the consequences of that failure is expressed by probabilities of effect criteria defined in Section 2.3.

The representative probabilities are defined somewhat differently for each category of system:

1. BPR_i = P(Event i/at least 1 hit) $\quad i = 1, \ldots, 4$
2. BPR_i = P(Event i/exactly 1 hit) $\quad i = 1, \ldots, 4$

$\sum_{i=1}^{4} BPR_i = 1$ as the probabilities are describing what will happen if damage occurs.

In LMP-3, the number of fragments hitting the component is assumed to undergo a Poisson distribution, i.e.,

$$P(\text{exact } \nu \text{ hit}) = \frac{\lambda^{\nu}}{\nu!} \text{EXP}(-\lambda)$$

where λ is the calculated average number of hits. We then derive, for both categories:

1. $P(\text{Event } i) = BPR_i[1 - \text{EXP}(-\lambda)] \qquad i = 1, \ldots , 4$
2. $P(\text{Event } 1) = 1 - \text{EXP}(-\lambda \cdot BPR_1)$

   $$P(\text{Event } i) = \text{EXP}(-\sum_{j=1}^{i-1} BPR_j \cdot \lambda) - \text{EXP}(-\sum_{j=1}^{i} BPR_j \cdot \lambda) \qquad i = 1, \ldots , 4$$

$$P(\text{Event } 5) = 1 - \sum_{i=1}^{4} P(\text{Event } i)$$

The two expressions are asymptotically equal when λ is small. The systems (subsystems) are combined -- with regard to effect -- into super-systems, which are in turn combined as though they were normal systems. Thus, the target as a unit is also a supersystem.

Damages in, for example, system j and system jj will occur according to the following scheme, with regard to the various events which occur as shown in Table 2:

Table 2. Combination of Subsystems

	Subsystem j 1	2	3	4	5
Subsystem jj 1	1	1	1	1	1
2	1	2	1	2	2
3	1	1	3	3	3
4	1	2	3	4	4
5	1	2	3	4	5

If system j and system jj are to be considered as redundant, the corresponding scheme will be as shown in Table 3:

Table 3. Combination of Redundant Subsystems

	Subsystem j: 1	2	3	4	5
Subsystem jj: 1	1	2	3	4	4
2	2	2	4	4	4
3	3	4	3	4	4
4	4	4	4	4	4
5	4	4	4	4	5

Example from Table 2: If Event 3 occurs for subsystem j (mission completed, aircraft lost), and Event 2 occurs for subsystem jj (mission aborted, aircraft returns to base), this means that Event 1 will occur with regard to the supersystem (mission aborted, aircraft lost).

In order to be able to formulate these tables mathematically, it is simpler to work with P (the most serious event which can occur for system j is Event k) = PP (j,k) rather than with P (Event k occurs for system j) = PS (j,k). The relationship between PS and PP is:

$$PP(j,k) = \begin{cases} \sum_{\nu=k}^{5} PS(j,\nu) & k \geq 3 \\ PS(j,2) + PP(j,4) & k = 2 \end{cases}$$

For the supersystem, we thus derive $PP(k) = PP(jj,k) \cdot PP(j,k)$ if the systems are not redundant.

For redundant systems, the results from Table 3 will be:

$$PP(2) = PP(j,2) + PP(jj,2) - PP(j,2) \cdot PP(jj,2)$$
$$PP(3) = PP(j,3) + PP(jj,3) - PP(j,3) \cdot PP(jj,3)$$
$$\begin{aligned} PP(4) = {} & PP(j,4) + PP(jj,4) - PP(j,4) \cdot PP(jj,4) + \\ & + [PP(j,2) - PP(j,4)] \cdot [PP(jj,3) - PP(jj,4)] + \\ & + [PP(j,3) - PP(j,4)] \cdot [PP(jj,2) - PP(jj,4)] \end{aligned}$$
$$PP(5) = PP(j,5) \cdot PP(jj,5)$$

The blast effect is transformed to some kind of fragment effect so the blast is treated in the same way as described here. As described in Section 4.5.1, the blast effect results in given probabilities for a

subsystem if the burst is within a certain volume or as totally damaged components (1000 fragment hits on a line segment) if the burst is close to the component. (Since 1000 effective fragment hits on any line segment are sufficient to assure complete destruction of the represented component and therefore operational system, that number of hits is used.)

4.6.2 Damage Integration Model in REFMOD

4.6.2.1 *Systems Components, Critically Vulnerable*

Component vulnerable areas are computed as:

$$A_v = \iint_{A_p} p(x,y)\, dy\, dx \tag{13}$$

where $p(x,y)$ = probability that target is defeated by impact of penetrator at point (x,y) in plane in which vulnerable area is to be measured

A_p = area of component projected into this plane.

These vulnerable areas are computed according to either of two definitions (at the user's option), component or component-incremental. In either case, as the penetrator proceeds along the shot line, the residual weight and speed are computed after each target component is encountered.

The shot line is located either randomly within a cell or at the center of the cell. The size of a cell is specified as an input to the shot line generation program. This cell size is usually two, three, or four inches on a side for aircraft vulnerable area determinations, but may be as small as one inch or as large as six inches. The results might be guide sensitive to the size of the cell.

Two definitions which apply are as follows:

- Component vulnerable areas are those vulnerable areas for which the individual component probabilities of kill are determined from the input conditional kill tables as functions of the residual weight and speed of the penetrator at impact with the component.

- Component incremental vulnerable areas are those vulnerable areas for which the individual component probabilities are determined as above and reduced by the probability that the target has not been defeated previously along the shot line. In effect, the component incremental vulnerable area for a given component represents the contribution that component makes to a total target vulnerable area for a specific attack aspect and kill definition.

Some vulnerable areas are based upon multi-fragment effects which are depicted by vulnerable area values which are a function of fragment density. Vulnerable area tables are stored as a function of fragment density.

Assuming that the expected number of lethal hits, E, on A_v have a Poisson distribution, the probability of A_v receiving one or more hits (component kill probability) is estimated by:

$$P_k = 1 - \exp(-E)$$

Generally, more than one fragment class has an opportunity to kill, say, the i-th component; therefore,

$$E_i = \Sigma E$$

and the component probability of kill is then:

$$P_{k_i} = 1 - \exp(-E_i)$$

4.6.2.2 Systems Components

If the vulnerable area of a component is not known and the fragments are not uniformly distributed over a surface, the following equations are used to calculate the component kill.

If one fragment is required to kill ($N_{req} = 1$)

$$P_{k_i} = 1 - (1 - P_{k_{hit}} \cdot PH)^{\lambda_b}$$

where $P_{k_{hit}}$ = conditional kill probability upon sustaining N_{req} fragment hits

λ_b = expected number of fragment hits

$$PH = \text{Poiss}\ (\lambda_b, N_{req}) = 1 - e^{-\lambda_b} \sum_{k=0}^{N_{req}-1} \frac{\lambda_b^{\,k}}{k!}$$

The probability of achieving at least N_{req} fragment hits, given an expected number of fragment strikes, λ_b

If N_{req} is greater than 1:

$$P_{k_i} = P_{k_{hit}} \cdot PH$$

Depending on type of warhead, different estimates are made to calculate λ_b. Notice that for these components, no calculations are made for fragment penetration.

4.6.2.3 Structural Components

Using the area removal criterion, a probability is calculated using:

$$P_{k_i} = 1 - e^{-PsL_F}$$

where Ps = probability of breaking structural member at a particular spot

L_F = length of structural member (in fragment sizes) covered by the fragment spray.

Using the energy density, there are two threshold values; a minimum value E_{min} required for any damage and a maximum value E_{max} required for $P_{k_s} = 1$. The calculated energy E at the component is tested against these criteria. In the remaining cases where some damage occurs to segments, their kill probabilities are:

$$P_{k_i} = \frac{E - E_{min}}{E_{max} - E_{min}}$$

4.6.2.4 Combinatorial Target Model

The components are grouped in systems and the systems in groups. The system definition is used to handle such problems as at least 3 of 4 systems having to be killed before the group is killed. If we use the system definition only to handle redundancy (all systems have to be killed before the group is killed) and assume that each system only contains one component, the component kills are combined in the following manner:

The kill probability, P_{k_m}, of each multiply vulnerable component group is computed, using the expression:

$$P_{k_m} = \prod_{i=1}^{N_c} P_{k_i}$$

where N_c = number of components (systems) in the group

P_{k_i} = kill probability of the i-th component (system) in the multiply vulnerable component group.

The kill probabilities of each multiply vulnerable component group and singly vulnerable component are combined, using the expression:

$$P_{k_{ct}} = 1 - \prod_{j=1}^{N_m} (1 - P_{k_{m_j}})$$

where $P_{k_{ct}}$ = total kill probability for the combined singly and multiply vulnerable components

N_m = number of components and component groups

$P_{k_{m_j}}$ = kill probability for the j-th component or component group

4.6.3 Comparison of U.S. and Swedish Damage Integration Model

In Table 4, a review is given of some of the equations used to get the probabilities of blast effect, structural kill and component kill. If the equations are not given, it is indicated whether the calculations will give a probability with a value between zero and one, or just end with either a zero or a one.

Many of the equations seem to be the same in both models, especially the component kills where both have assumed the hits on the component to have a Poisson distribution.

On the other hand, there are cases where in one program calculations give a probability of $0 \leq p \leq 1$ and in the other programs the same problem only gives a $p = 1$ or $p = 0$. Therefore, it is difficult to make a direct comparison of the models but the greatest differences are the treatment of the fragment penetrations and the damage criteria. (Fragment penetration is discussed in Section 4.2).

Table 4. Review of Swedish and U.S. Damage Integration Model

PROBLEM	COVART/REFMOD	LMP-3
Blast Effect P_B		
External Burst Point	If the burst is within a given volume, $P_B = 1$; otherwise $P_B = 0$.	If the burst is within a given distance, the probability of the fragment penetration increases.
Internal Burst Point	If there is a contact kill, $P_B = 1$; otherwise $P_B = 0$.	1) If the burst is within a given volume $P_B = P$. 2) If a component is close enough Component Kill = 1. 3) Probability of fragment penetration is increased.
Fragment Structural Kill, P_s	1) Area removal criterion $P_s = P$. 2) Energy density criterion $P_s = P$.	Not treated.
Component Kill P_c		
Will the fragment reach the component?	If the fragment penetration equations used along the shot lines give a residual mass and velocity $P_{pen} = 1$; otherwise $P_{pen} = 0$.	Probability calculated from the structure's fragment retardation properties $P_{pen} = P$.
Will the fragment defeat the component? (Given a hit)	Kill probability of the component given as a function of the fragment size and velocity $P_{k/h} = P$. (Based on U.S. damage criteria)	If any part of the component can be defeated if hit by fragments, that part is represented as an area A, which can be compared with $P_{k/h}$. (Presented area) A is only given for a reference fragment. Each component also has a shield and the fragment momentum is decreased by the momentum the fragment would need to perforate that shield before calculating P_{pen}

Table 4. (Continued)

PROBLEM	COVART/REFMOD	LMP-3
The expected number of lethal hits if the component is within the fragment beam.	$E = \frac{Q \cdot A_v}{S} = \frac{Q}{S} \cdot P_{pen} \cdot P_{k/h} \cdot A_p$ where Q = lethal number of fragments within the fragment beam S = spherical area approximating the fragment beam F = surface of a frustum A_p = presented area of component	$\lambda = \frac{Q \cdot A}{F} \cdot P_{pen}$ where Q = lethal number of fragments within the fragment beam S = spherical area approximating the fragment beam F = surface of frustum A_p = presented area of component
What will happen if the component is damaged?	Those components that will cause the kill category studied are described $P_D = 1$.	The components are grouped in subsystems and to each subsystem is given a probability P_D = BPR. (Swedish damage criteria)
Set of non-redundant components	$P_{cj} = 1 - e^{-E_j}$ component j N Components $P_c = 1 - \pi_j^N (1 - P_{cj}) =$ $\left(1 - \pi_j^N e^{-E_j} = 1 - e^{-\Sigma_j^N \cdot E_j}\right)$	P_{cj} is not calculated. N Components $P_c = BPR_i \left(1 - e^{-\Sigma_j^N \lambda_j}\right)$ BPR_i = P(Event i/at least 1 hit)
Set of redundant components (N components)	$P_{cj} = 1 - e^{-E_j}$ N redundant components $P_c = 1 - \left(1 - \pi_j^N P_{cj}\right) = \pi_j^N (1 - e^{-E_j})$	P_{cj} is not calculated. N redundant components; assume $P_D = 1$ $P_c = \pi_j^N (1 - e^{-\lambda_j})$
Multi-fragment components	A_v is a function of fragment density, the number of fragments per unit area.	$P_c = 1 - e^{-BPR \Sigma_j^N \lambda_j}$ BPR = P(Event 1/exactly 1 hit)

The U.S. damage criteria are given for components. These criteria are easy to relate to fragment size and velocity but are difficult to relate to malfunctioning of systems. The Swedish damage criteria are given for subsystems. These criteria are difficult to relate to fragment size and velocity but easy to relate to malfunctioning and the pilot's reaction to malfunctions.

Furthermore, the Swedish damage criteria and their relations to subsystems make it possible in the same run to treat all the components of the aircraft. The results of one run, therefore, give the complete answer to the questions if the aircraft is lost or not, and whether it has been able to complete its designated mission.

5.0 COMPARATIVE COMPUTER RUNS

Possibilities for making completely comparative runs were limited by security problems, time available, and the differently defined kill categories. However, the results presented here are those which in each country could have been used in a vulnerability assessment. The conclusions are based upon these results and, therefore, a comparison is believed to be valid.

5.1 INPUT SELECTED

The initial consideration used to select target aircraft for the comparison computer runs was that the target descriptions were available both in Sweden and the U.S. since the time required and associated costs to generate new descriptions in either country would be too great for this project. In addition, the target descriptions had to be unclassified to eliminate the security problems in both countries. For an effective evaluation, we felt we should include at least three types of aircraft -- a high-performance fighter, a long-range bomber, and a helicopter. The only aircraft which met the requirements of an existing target description in both countries which was also unclassified for the same aircraft, was a long-range bomber. Even for this aircraft, security requirements can only be met by refraining from describing the details of the target descriptions as related to specific components and by refraining from naming the aircraft.

Since there were no more existing Swedish and American target descriptions for the same aircraft in both the fighter and helicopter categories, we had to select similar aircraft for these. Again, security considerations preclude the naming of the selected aircraft, but the fighter aircraft are both single-engine, high-performance but obsolete jets and the helicopters are both single-engine and obsolete. In both categories, the twin-engine aircraft are roughly equivalent in performance, weight, and construction.

The target descriptions for these aircraft were generated within each country based upon the information available therein. Also, the long-range bomber aircraft descriptions are ostensibly for the same aircraft, which was actually foreign to both countries. The information about that aircraft available in each country could, therefore, have differed as much as target descriptions of two different but similar aircraft made in either one of the countries. An evaluation of the components used in each country for this bomber leads one to believe that the aircraft data used in each country were quite similar.

To determine the effects which warhead size would have upon the comparative assessments, two typical warheads were selected; a larger warhead representative of a medium surface-to-air missile with a conventional high explosive fragmentation warhead and a smaller warhead representative of a small antiaircraft cannon shell. Both were presumed to have proximity fuzing which was simulated by inputting a matrix of burst points below the aircraft along trajectories parallel to the aircraft flight path but in the opposite direction. None of the bursts were assumed to be within the aircraft.

The large warhead was presumed to launch approximately 17,000 two-gram, preformed, steel fragments in a relatively wide band and the small warhead approximately 600 0.25 g spherical tungsten fragments in a relatively narrow band. In addition, the small warhead emits approximately 900 uncontrolled steel fragments, varying in weight.

For these two warheads, the identical number, size and material of fragments were input into LMP-3 and REFMOD. Also the same fragment pattern boundaries and velocities due to detonation were input into both models, as were the same missile/projectile and aircraft velocities. Therefore, the threat inputs were identical.

To determine the sensitivity of the programs to some specified parameters, some calculations were made for fragments evenly spread all over the target. The calculations were made for three striking velocities (1000, 2000, 3000 m/s), three fragment densities (0.1, 1, 10 fragment/m^2), and four striking directions. Two types of fragments were used; steel cubes of 1 cm^3 volume and tungsten spheres with a diameter of 3 mm.

5.2 EVALUATION OF COMPARATIVE RUNS

5.2.1 Warheads Against the Bomber

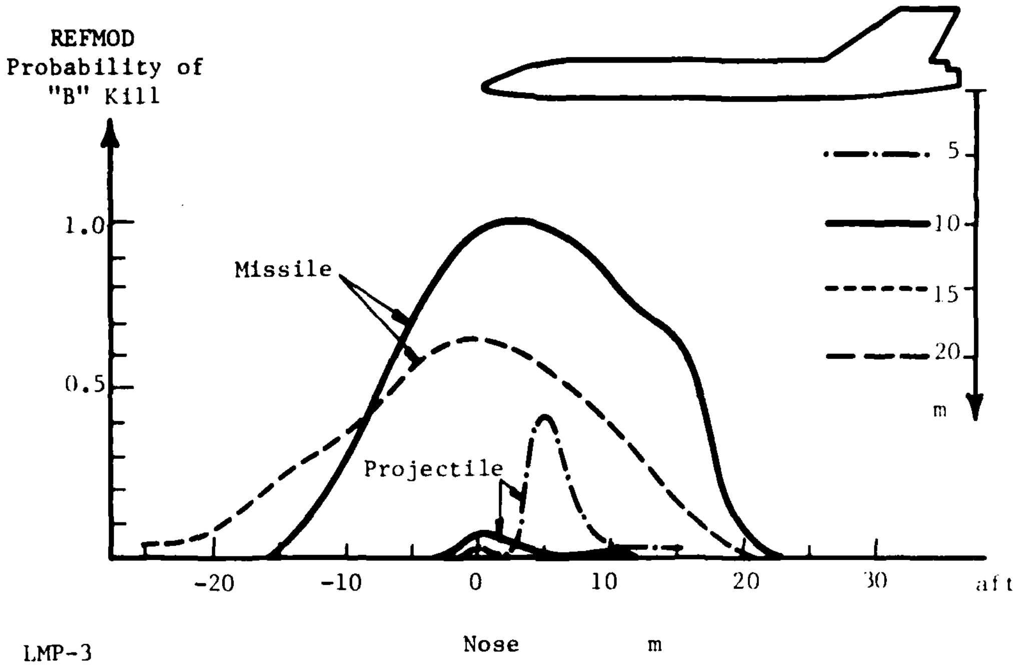
The scenario for the Swedish target description of the bomber is that, at the moment of impact the aircraft still has about 10 minutes to fly before reaching the target site and needs 30 minutes to reach a friendly landing field. As there is a relatively long time before reaching the target site, the pilot can, if the aircraft is damaged, decide not to go on, but instead to try to reach the landing field.

For the U.S. model, the vulnerable area tables generated with a three-inch grid, which were available were given for "K," "A" and "B" kills and mission kill. The "A" and "B" kill results were essentially the same. The

mission kill included the same components as the "K" kill and also the components needed to deliver the weapons.

In Figure 15, the REFMOD "B" kill (30 min.) results are compared with the LMP-3 probabilities of Event 1 + Event 3. The diagrams illustrate the variation in kill probability along the trajectories for the small and large warhead. This comparison should be valid as in this case the target descriptions are made for the same aircraft and the kill categories are related to the same time. As shown in Figure 15, LMP-3 always gives higher probabilities than REFMOD, the curves rise almost at the same place, the peak is about 5 meters earlier and the decrease comes about 15 meters earlier in REFMOD than in LMP-3. It is difficult to explain in detail what is causing the differences. However, the details of the target description and which components have been considered critical are important. The earlier drop in the REFMOD curve must be caused by fewer critical components in the tail of the U.S. description than in the Swedish. Figure 16 shows the Swedish target description of the bomber. A brief listing of the components, and whether they are considered redundant is shown in Figure 17 for the U.S. description and in Figure 18 for the Swedish. These listings show that the Swedish description might contain more of the flight control system than the U.S. description. Because this system has many components in the tail, this might be the explanation of the later drop in the LMP-3 curve. The different treatment of this system might also be one of the reasons for higher kill probabilities in the Swedish model. However, here the reasons can be many, e.g., different damage criteria, or different treatment of fragment penetration. It is impossible without more information and further investigations to determine which are the main reasons.

The mission kill criteria are compared in Figure 19. Here the definition and use of the criteria are different in each country so there are at least two reasons for the Swedish probabilities to be higher. In the Swedish scenario, the aircraft has to survive for at least 10 minutes after impact to complete its mission, and in the U.S. a mission kill includes only "K" kill (30 sec.). Furthermore, in the Swedish model, the pilot's reaction is considered, and that means that some damages are included which do not necessarily kill the aircraft but still might force the pilot to return. This explains some of the differences in the component lists (Figures 20 and 21) where, for instance, in the Swedish list the engines are no longer considered redundant.



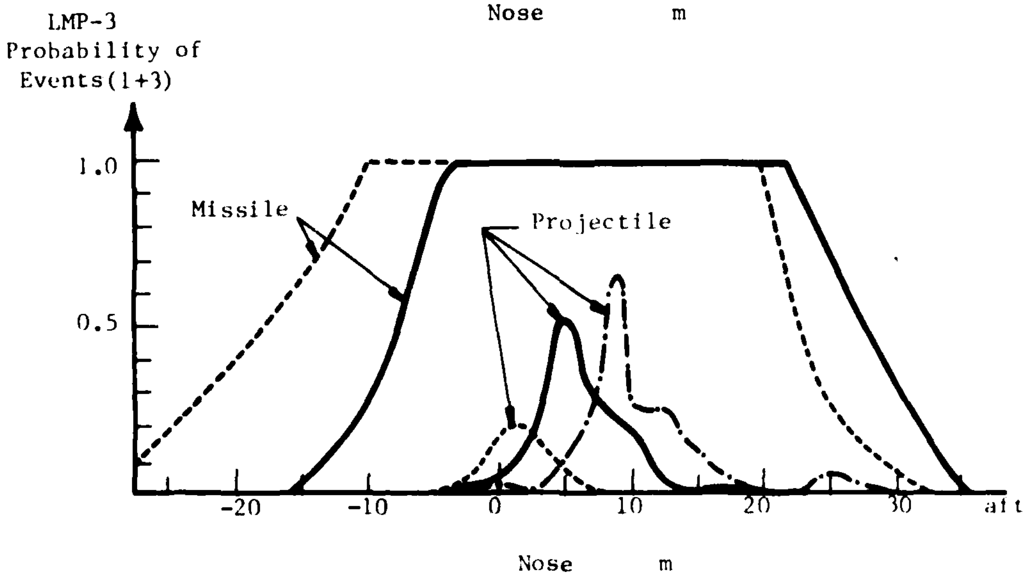


Figure 15. Warheads Against the Bomber for Attrition

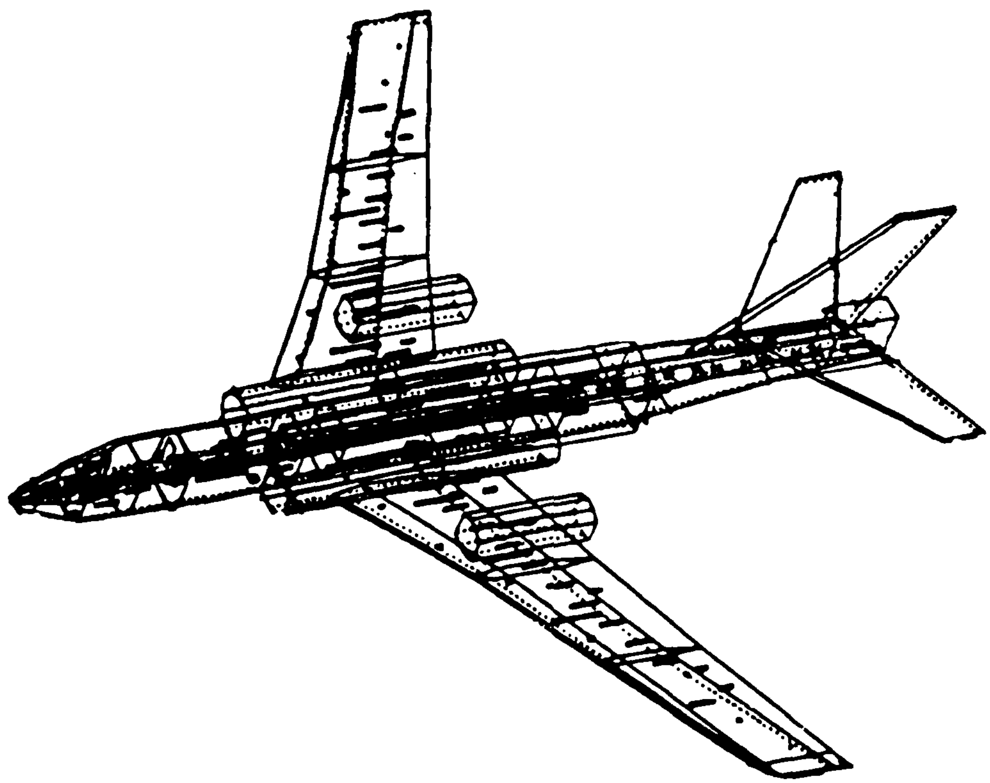


Figure 16. Swedish Target Description of Bomber

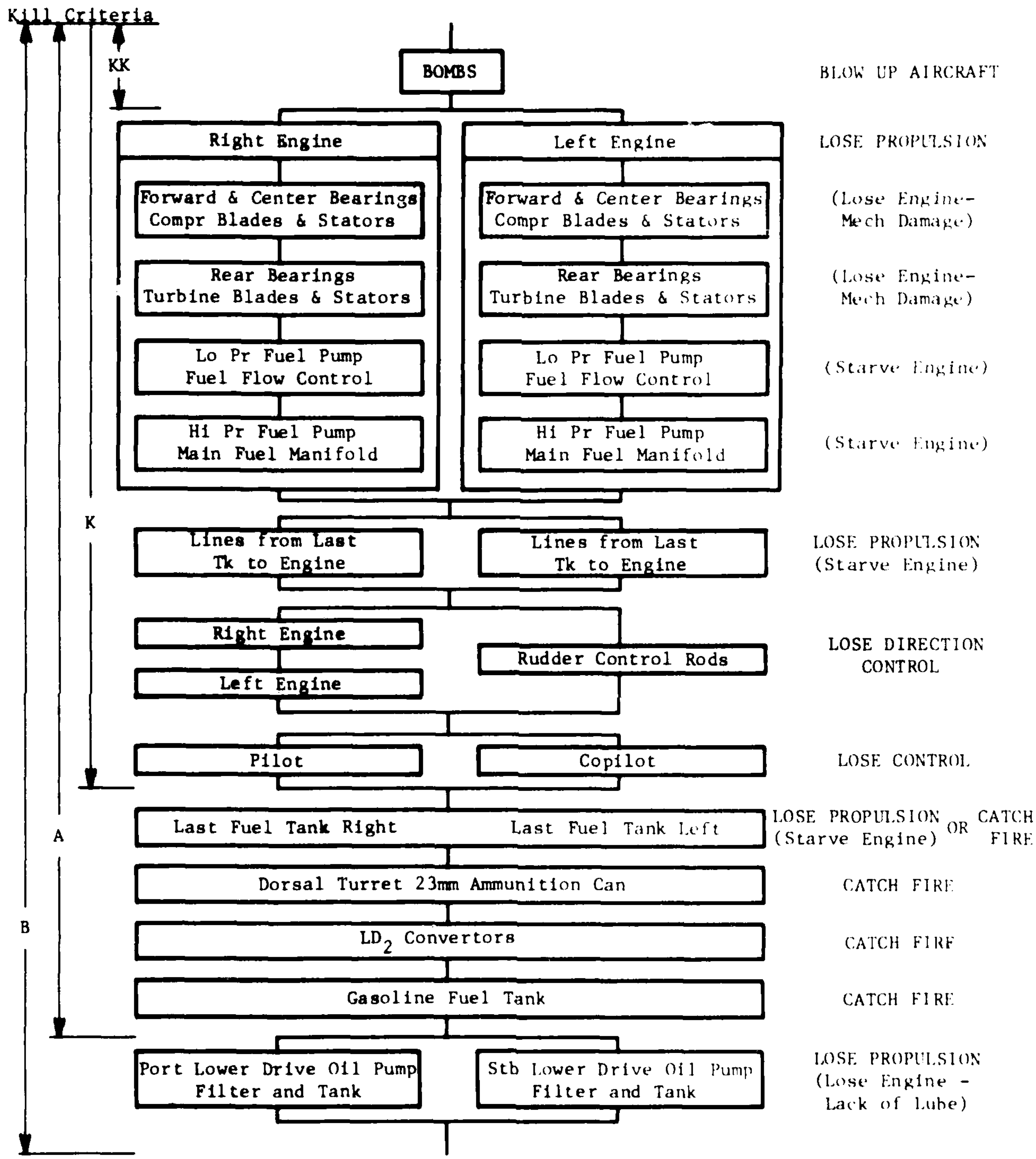


Figure 17. Component List of the U.S. Description of the Bomber for Attrition

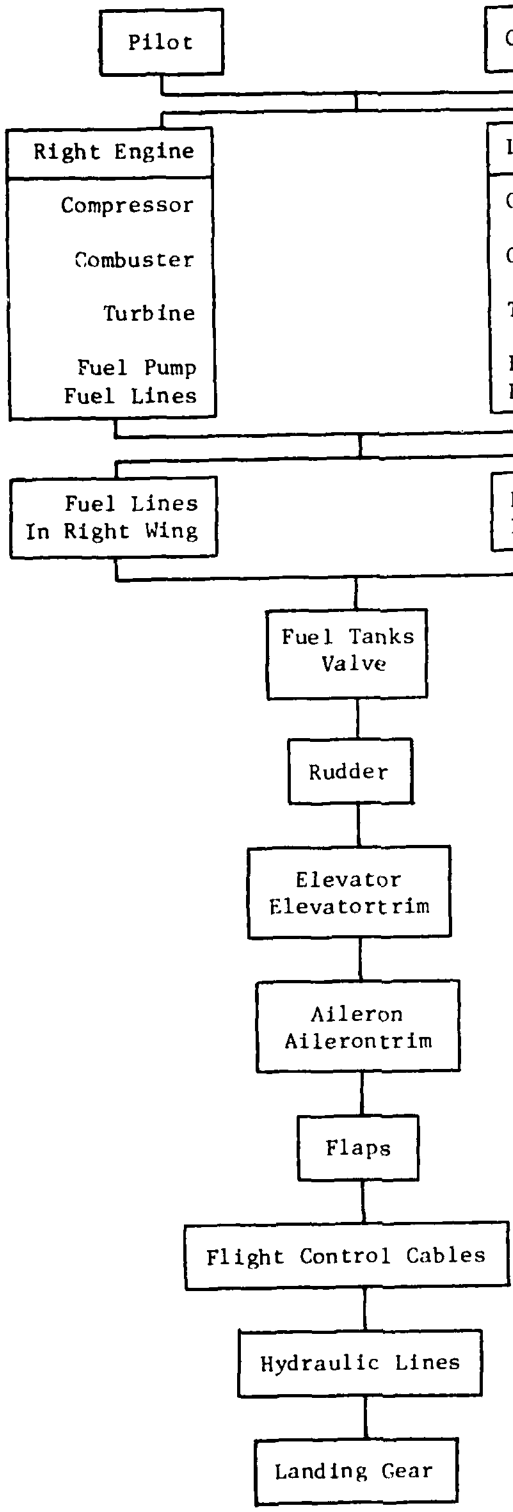


Figure 18. Component List of Swedish Description of Bomber for Attrition

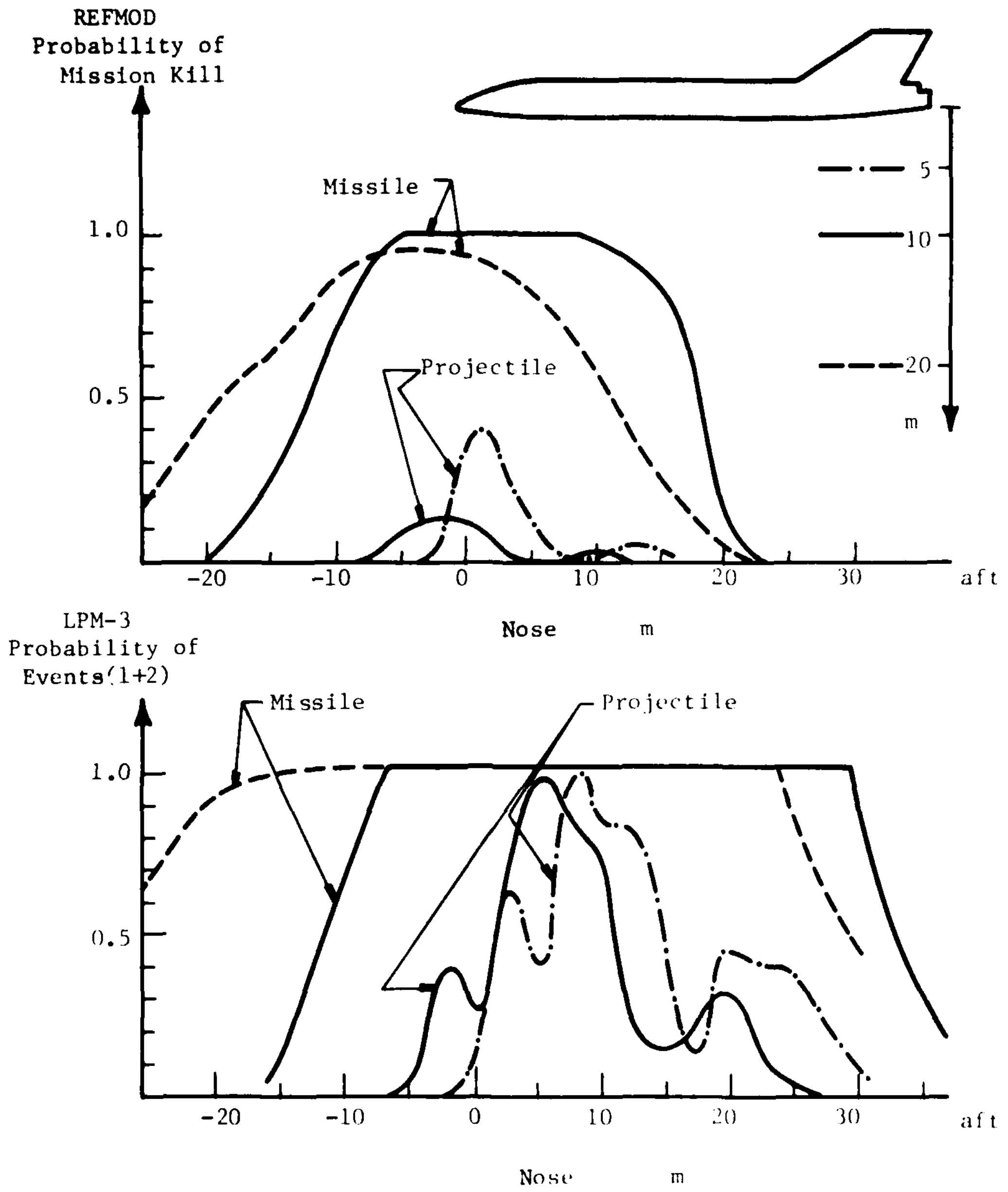


Figure 19. Warheads Against the Bomber for Mission Kill

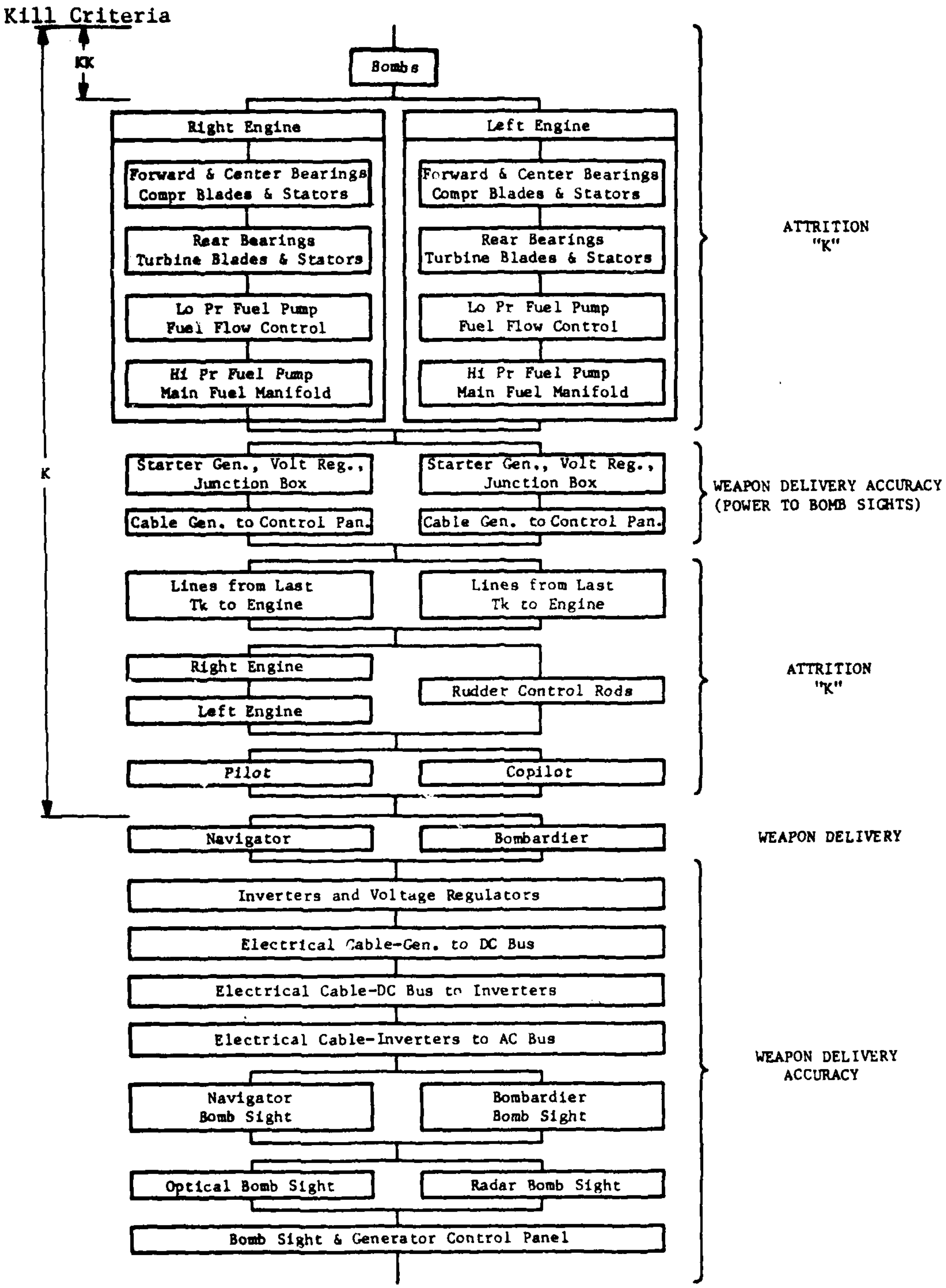


Figure 20. Component List of the U.S. Description of the Bomber for Mission Kill

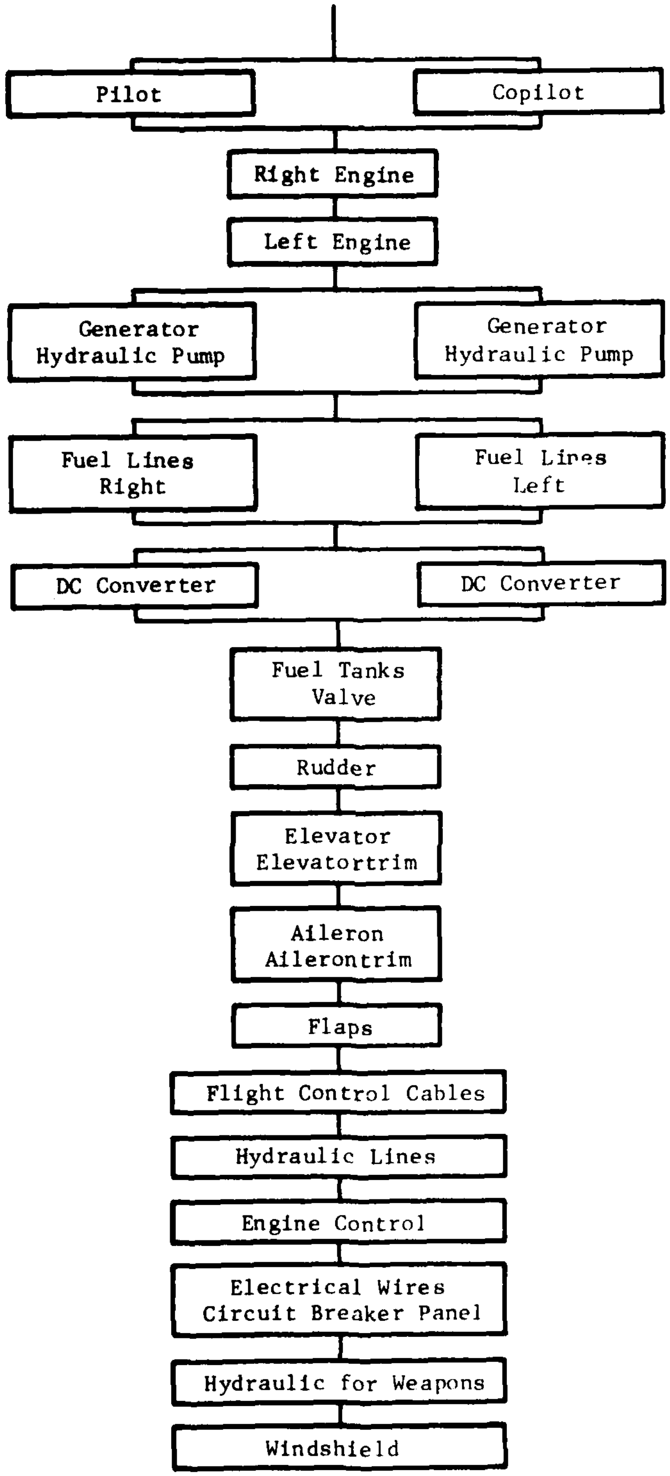


Figure 21. Component List of the Swedish Description of the Bomber for Mission Kill

Even though there are explanations for the higher kill probabilities of the Swedish model, it is worth considering that decisions in each country are based upon those numbers. Using the LMP-3 results, the conclusion would be reached that the missile would have enough effect even if the miss distance is 20 m. Based on REFMOD results, the conclusions might be that the miss distances cannot be more than 10 m. If the mission kill only is used as the effective criterion, the LMP-3 results show that a projectile at a miss distance of 10 m has good effect. The highest probability of mission kill under those circumstances from REFMOD is about 0.1; hence, conclusions would probably be quite different than if the LMP-3 results were used.

5.2.2 Warheads Against the Fighter

The Swedish target description for the fighter includes the assumption that the impact is only one second before the pilot is going to deliver the rockets. It will take more than 10 minutes to reach a landing field, and the navigation system is not necessary.

The U.S. vulnerable area tables for the fighter were only available for "K" kill (30 sec). For the fighter no real comparison is possible as the target descriptions are based on different aircraft and the criteria are not related to the same time. The Swedish attrition (Event 1 + Event 3) should have been compared with "A" kill, but instead in Figure 22 it is compared to "K" kill. In spite of these differences, again these numbers might be the ones that would be used in an evaluation of warhead effectiveness. In Sweden the category attrition (Event 1 + Event 3) is the most used and in the U.S., either "K" or "A" kill. As they should be, the LMP-3 probabilities are higher than the REFMOD "K" kill. But as in the case of the bomber, this means that the same differences in conclusions would appear if these effective criteria had been used in each country.

If instead, the "K" kill is compared with the probability of only Event 1 (Figure 23) the curves are almost the same. The criteria are not the same (LMP-3 - mission not completed, lost within 10 minutes; REFMOD - lost within 30 seconds) but the results and the conclusions based on them would be the same.

5.2.3 Warheads Against the Helicopter

The Swedish target description is based on the assumptions that the helicopter is transporting personnel and has at the moment of impact still

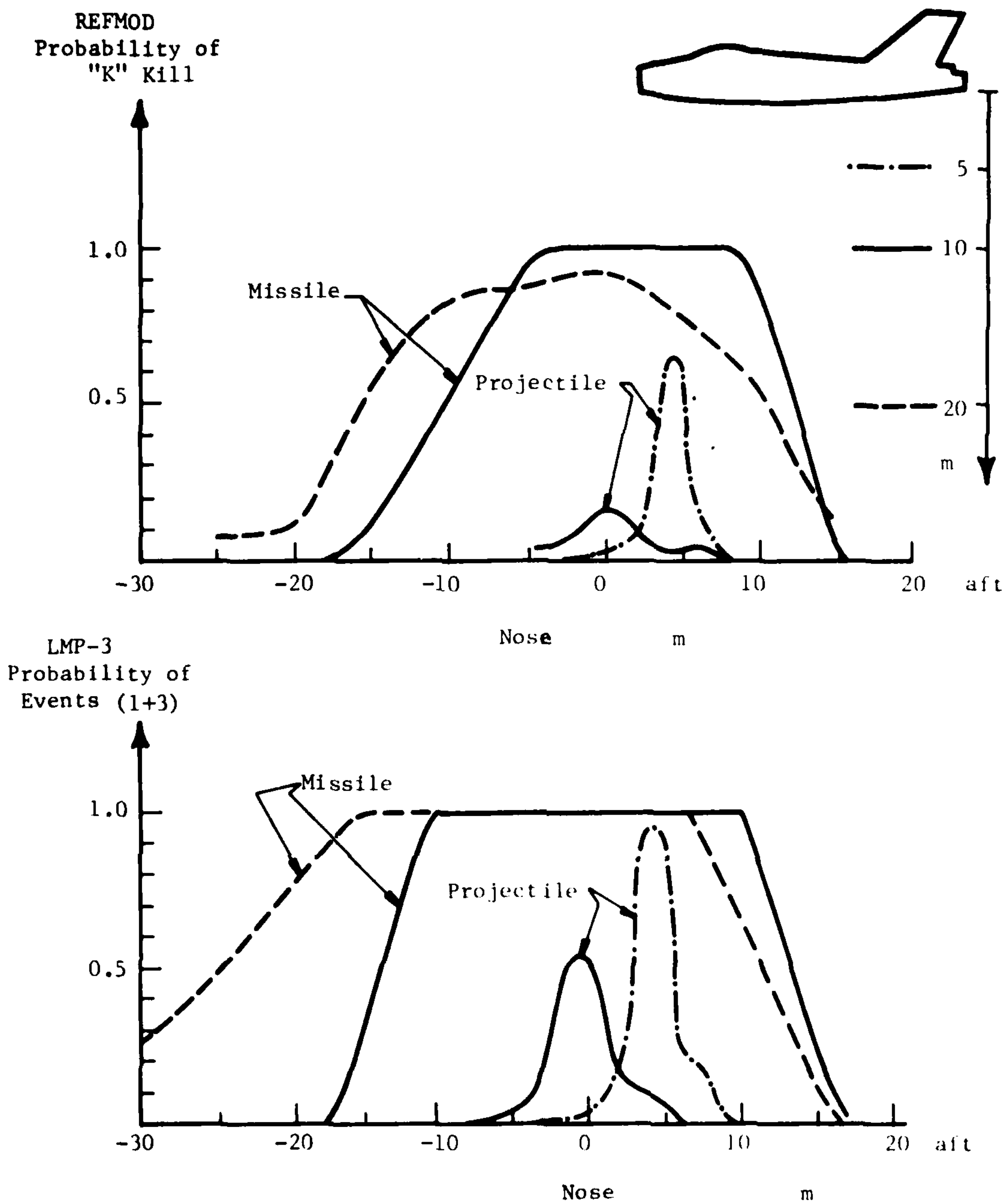


Figure 22. Warheads Against the Fighter for Attrition

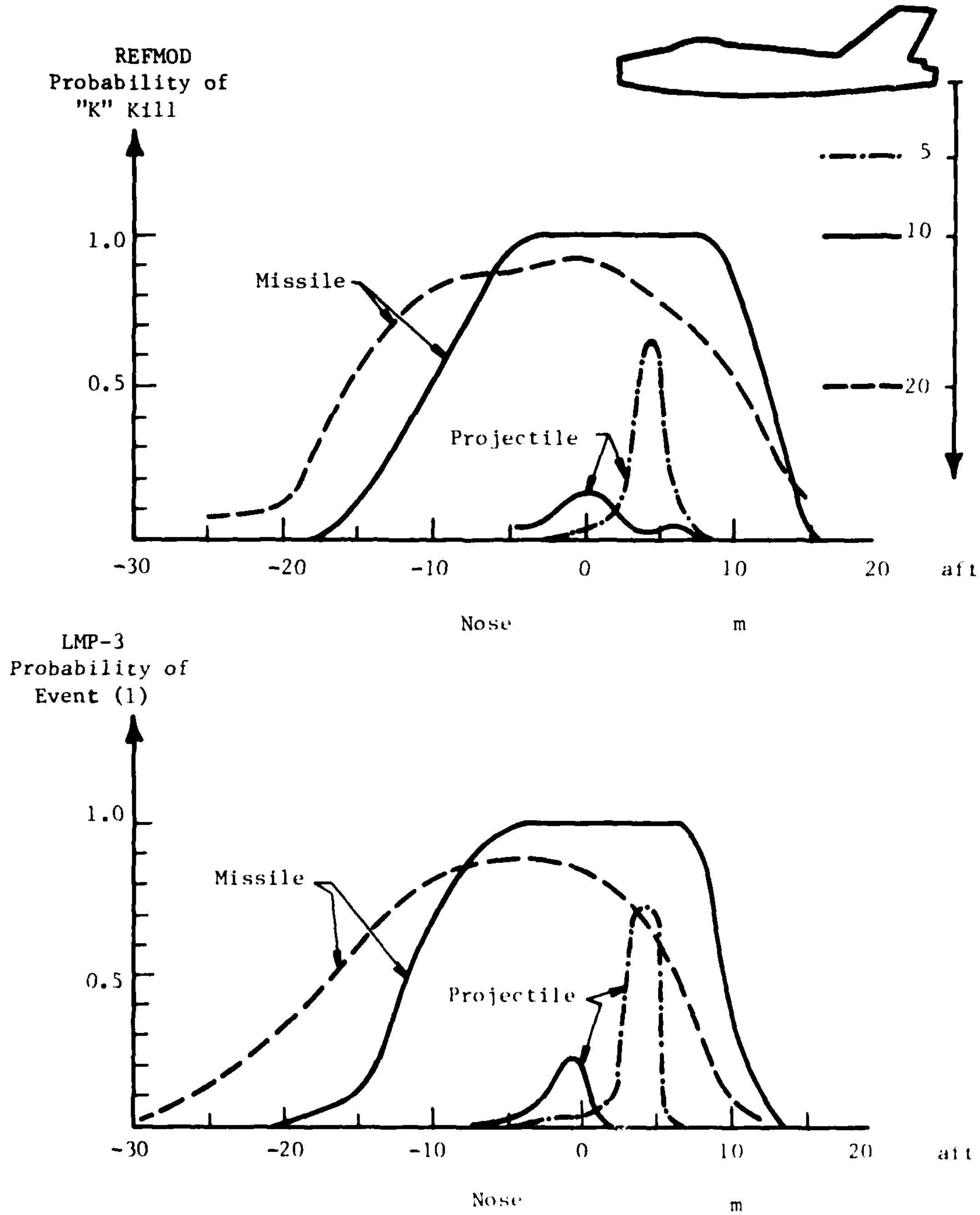


Figure 23. Warheads Against the Fighter for Attrition and Mission Kill

20 minutes to fly to complete the mission. To reach a landing field will take less than five minutes.

(Waiting for REFMOD data.)*

(Figure 24)

5.2.4 Fragments Spread Evenly All Over the Targets

If only one parameter at a time is varied, it is possible to get the influence of that parameter on the kill probability. The kill categories used for the Swedish model have for all three targets been attrition (Event 1 + Event 3). For the U.S. model different categories have been used for each target; for the bomber "B" kill, for the fighter "K" kill, and for the helicopter "_" kill.

All the results are shown in Figure 25 for the steel cubes and in Figure 26 for the tungsten spheres. The kill probabilities are given as a function of the striking velocity for all fragment densities and striking directions.

A brief review of how the kill probabilities (P_k) are dependent on the parameters, striking velocity, number of fragments, and striking direction is given in Table 5. There we state whether the kill probability has increased, been unchanged, or decreased when the striking velocity is increased from 1000 m/s to 3000 m/s. A reduction would appear if the fragments start to break up and, as this problem is not treated in LMP-3, the LMP-3 probabilities cannot decrease when the velocity ~~is increased~~. (This is not the case in REFMOD; see Section 4.2.) If P_k stays unchanged, this means that no additional critical components are reached. In the Swedish model, it also means that the components are reached with a probability already equal to one for the velocity 1000 m/s, otherwise that probability would have increased and so would the P_k. If P_k is unchanged for REFMOD then that also means that the damage criteria are not dependent on the velocity within this range.

The calculated probabilities (P_k) from both models, show good agreement with the following equation:

$$P_k = 1 - e^{-nx}$$

where n = the given number of fragments per unit area (see Section 4.6)

x = the total vulnerable area in that direction, or for LMP-3, a comparable parameter.

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* Data will be generated by the U.S. Government at a later date to complete the comparison.

(WAITING FOR REFMOD DATA)*

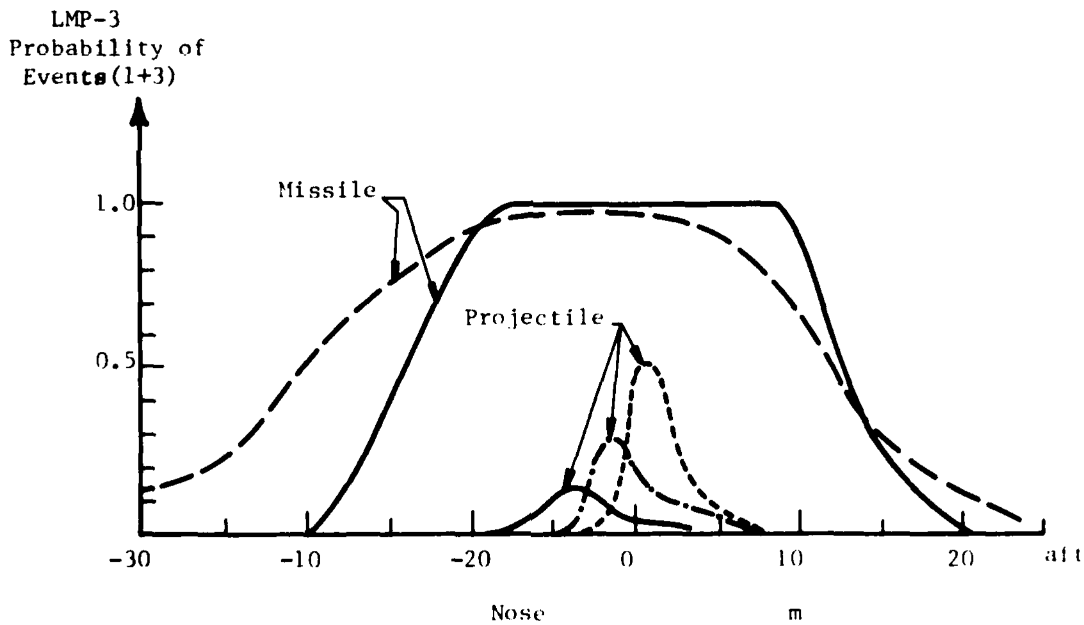

Figure 24. Warheads Against the Helicopter for Attrition

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* Data will be generated by the U.S. Government at a later date to complete the comparison

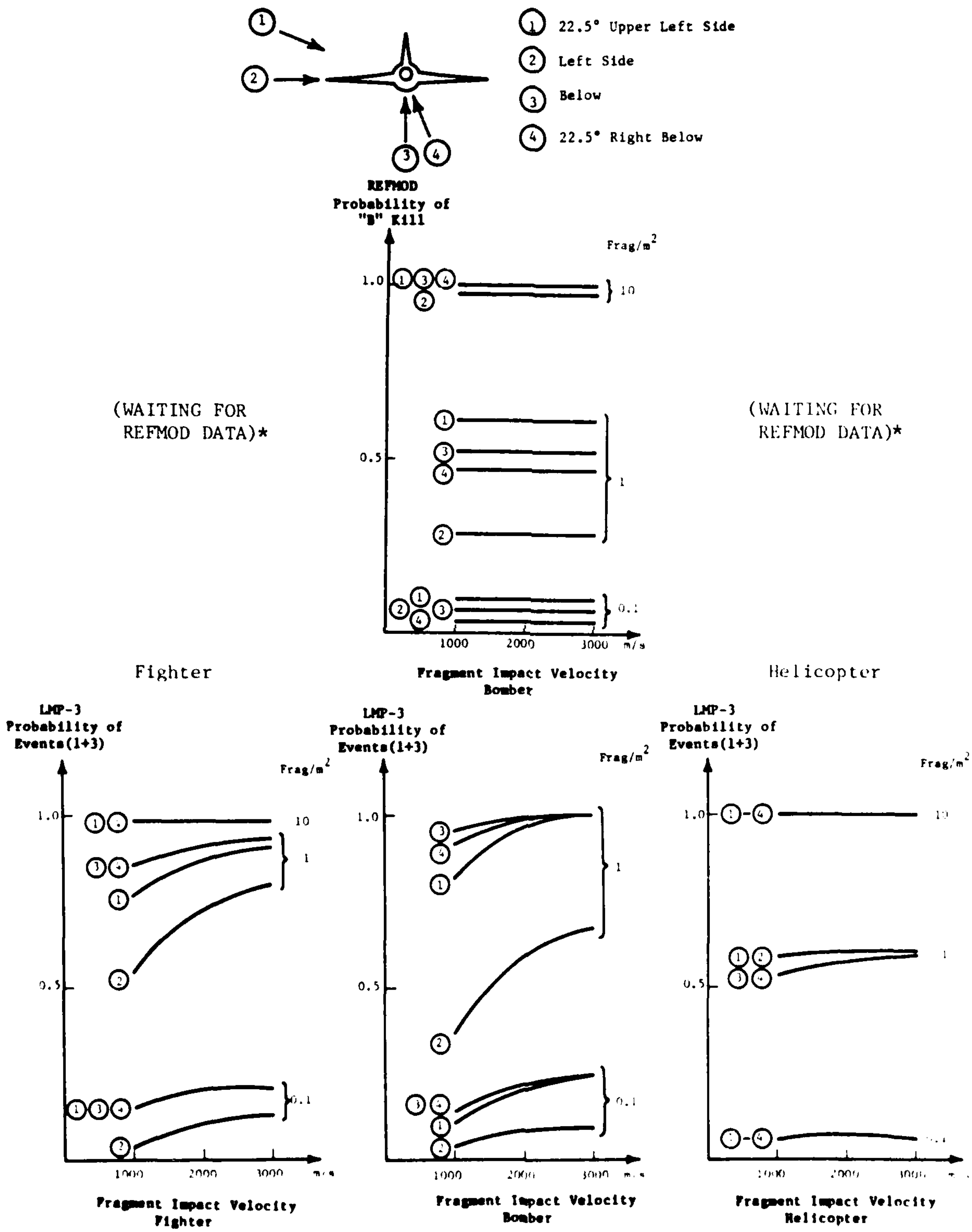
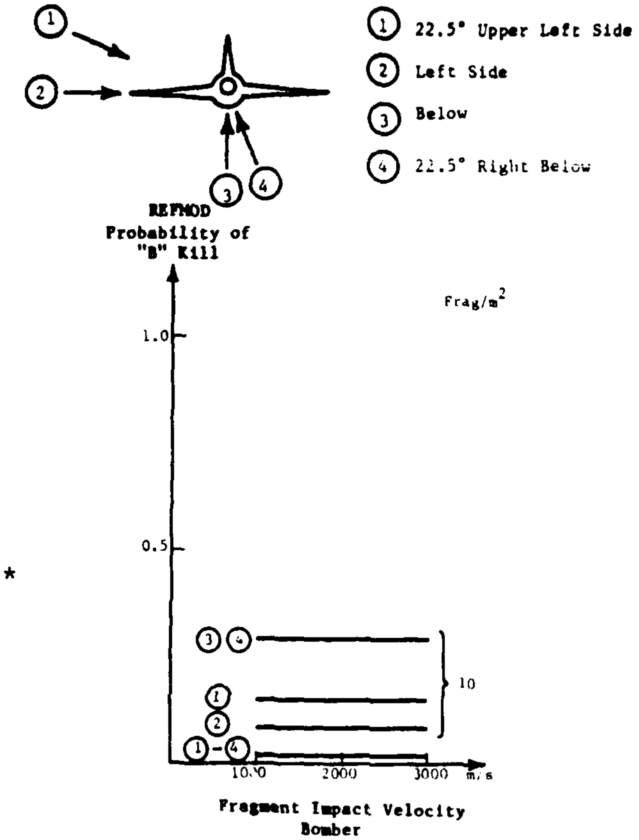


Figure 25. Steel Cubes Evenly Spread All Over the Targets

* Data will be generated by the U.S. Government at a later date to complete the comparison.



(WAITING FOR REFMOD DATA)*

(WAITING FOR REFMOD DATA)*

Fighter

Helicopter

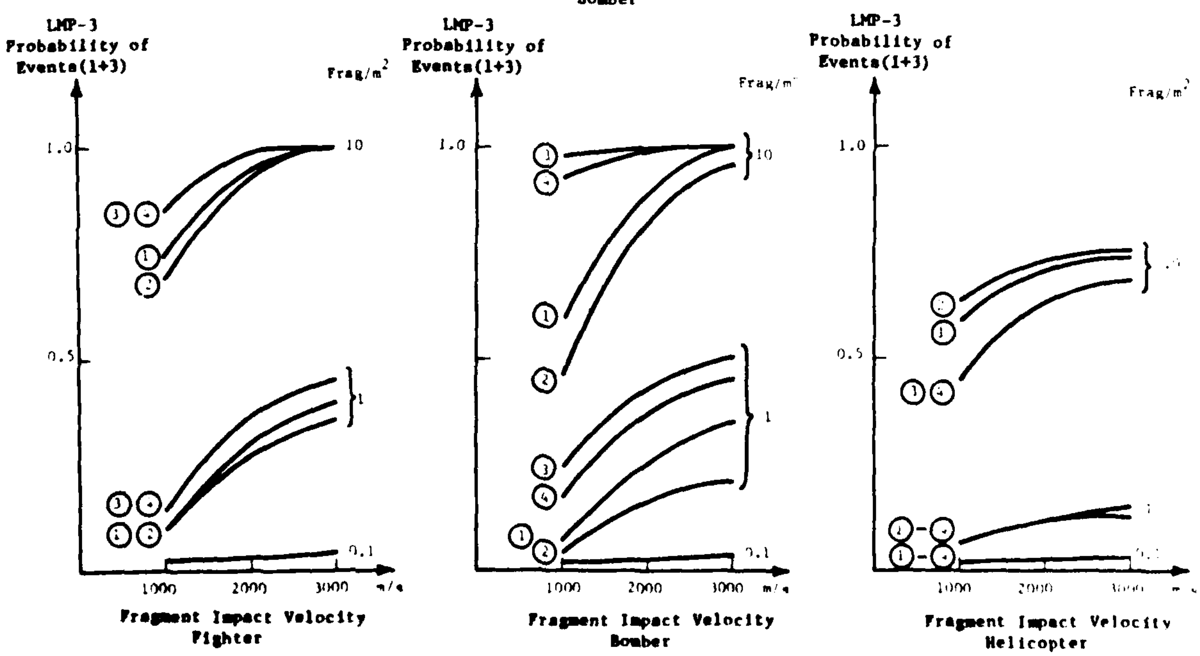


Figure 26. Tungsten Spheres Evenly Spread All Over the Targets

* Data will be generated by the U.S. Government at a later date to complete the comparison.

Table 5. Influence on the Kill Probability of Different Parameters

Parameter	Fragment	Bomber LMP-3 P(1+3)	Bomber REFMOD "B" Kill	Fighter LMP-3 P(1+3)	Fighter REFMOD "K" Kill	Helicopter LMP-3 P(1+3)	Helicopter REFMOD
Changes in P_k when increasing striking velocity from 1000 m/s to 3000 m/s	Steel Cube	Increasing	Unchanged	Increasing	(WAITING FOR REFMOD DATA)*	Almost Unchanged	(WAITING FOR REFMOD DATA)*
	Tungsten Sphere	Increasing	Unchanged	Increasing		Increasing	
Number of fragments per square meter needed to reach P_k=1	Steel Cube	1	3	Slightly more than 1		3	
	Tungsten Sphere	4	100	4		20	
Direction which gives highest P_k	Steel Cube	Below	22.5° upper left side	Below & 22.5° right below		Left Side	
	Tungsten Sphere	Below	Below	Below & 22.5° right below		Left Side	
Direction which gives the lowest P_k	Steel Cube	Left Side	Left Side	Left Side		Below	
	Tungsten Sphere	Left Side	Left Side	Left Side		Below	

* Data will be generated by the U.S. Government at a later date to complete the comparison.

If P_k is plotted against n, the number of fragments needed to give $P_k = 1$ can be estimated. As the runs were only made for 0.1, 1, and 10 fragments/m^2, the statements in Table 5 are of that accuracy. The numbers are, furthermore, for a striking velocity of 3000 m/s and the direction which gives the highest probability. As the kill probabilities are a function of the fragments per unit area times the vulnerable area, it means that if more fragments are needed, s smaller vulnerable area has been used, and vice versa. The differences between the models which sometimes are quite large, can originate from the damage criteria used for any specific component, or the number of components described, or the treatment of fragment penetration capability. Which one has had the greatest influence is impossible to say without examining the details of the target descriptions.

The striking directions which give the highest and the lowest probabilities are also listed in Table 5. This will indicate whether shielding is treated differently in both models.

6.0 SIMILITUDE MODEL BASED ON SWEDISH PARAMETERS

The computer programs which are used today to solve aerial target vulnerability (ATV) problems are complicated and the demand of manpower and time to use these programs is tremendous. This is especially true if the study is for a target vehicle which is not described in the computer program. Such descriptions often require more than a year before the first results are available. The purpose of this discussion is to obtain model laws and scaling laws which are applicable to those problems and which can be used in a "quick and dirty" method. The Pi Theorem [19] will be used to combine fourteen independent parameters through ten pi terms into ONE equation which will predict the problem vulnerability of an aircraft. Three empirical constants will be needed to relate the relative probability computed to actual aircraft. These constants will be obtained using the evenly distributed, parallel trajectory fragment data generated by LMP-3 for both steel and tungsten fragments impacting fighter, bomber and helicopter targets (see Figures 25 and 26). Thus we will use 14 independent variables and three empirical coefficients to compute the desired dependent variable, probability of an attrition kill.* Since this is a "first attempt," the problem has been limited to the effect of fragments striking the target from specified directions. This makes the equation sensitive to attack aspect since the target presented area, A, varies with attack aspect. The model discussed here is not to be regarded as a final solution but rather as an example which demonstrates the feasibility of this approach. Note that the assessment results from the Swedish computer program, LMP-3 [4] have been used.

6.1 PARAMETERS OF IMPORTANCE

The results from the Swedish computer program are presented for five events:

(1) Mission aborted - aircraft lost

(2) Mission aborted - aircraft returned to base - repairs required prior to next mission

(3) Mission completed - aircraft lost

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* A fifteenth variable is listed in Table 6 but is not independent of the others. A fourth empirical constant is indicated in the equation, but since that constant was equated to unity in the curve fit, it is essentially ignored.

(4) Mission completed - aircraft returned to base - repair required prior to next mission

(5) Mission completed - aircraft returned to base - aircraft available for next mission.

Only the probability (P) of Events 1 plus 3, which means the aircraft was lost either before or after completing the mission has been used in this demonstration. As only the effect of fragment impacts has been considered, the parameters necessary to describe the threat are: fragment size (D,d), fragment material density (ρ_p), fragment striking velocity (V_o), and as the fragments are assumed to be evenly spread, the number of fragments per unit area (n).

The purpose has been to describe the target with parameters which are unclassified (with reference to security requirements) and for which the values can be easily determined. The size of the target is defined by its total mass and volume (M,V). The volume can be estimated using drawings showing three views of the target. As the fragments can hit the target from different directions, the presented area (A) of the target in those directions is necessary. This makes the assessment sensitive to attack aspect. Since the fuel system is an important system, and since the damage mechanism for this system might be different from the other aircraft systems, this system has been treated separately. The mass of the total internal fuel capacity (M_f) and the mass of the remaining fuel at the moment of impact (M_{FR}) have been used. In addition to just the total mass of these systems which is a measure of the geometric size, some densities are used. The densities are density of the fuel (ρ_F), and average density of the material of all the components except the fuel (ρ_m). To obtain the fragment penetration capability in aerial targets, an average target material strength (S_m) is used. A complete list of parameters is shown in Table 6.

6.2 PI TERMS OF INTEREST

The model has to give the influence of the size, the penetration capability, and the number of fragments on the probability of attrition kill for certain target. The pi terms will identify those parameters of the fragments with similar ones of the target and also characteristics of importance of each target.

Table 6. List of Parameters

Symbol	Parameter	Fundamental Units of Measure
n	Number of fragments per unit area	$1/L^2$
V_o	Striking velocity of fragments	L/T
D	Presented area of fragments	L^2
ρ_p	Fragment material density	FT^2/L^4
d	Fragment diameter	L
A	Presented area of target	L^2
M	Total mass of target	FT^2/L
M_F	Mass of fuel	FT^2/L
M_{FR}	Mass of remaining fuel at moment of impact	FT^2/L
ρ_m	Average density of component material	FT^2/L^4
ρ_F	Fuel density	FT^2/L^4
S_m	Average shear strength of all target material	F/L^2
h_o	Average skin thickness of the target	L
V	Total volume of target	L^3
P	Kill probability	λ

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COMPARISON OF U.S. AND SWEDISH AERIAL TARGET VULNERABILITY ASSE--ETC(U)
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Since the fuel system is treated separately from the rest of the target, there will be some pi terms with two sets; one for the fuel system and one for the rest of the aircraft systems. A complete list of pi terms is given in Table 7, with a brief description of the significance of each term.

The number of fragments hitting each part will be given as the number of fragments per unit area times some representative area of the system [Terms (2) and (3)]. That area will be given by the mass divided by the density to the 2/3 power which means that the area will be the same for all attack aspects. There are two reasons for this: the terms are used when the fragments are assumed to have a very high velocity and as the break up of a fragment is not treated in the Swedish model, the fragments will have a very high penetration capability and hit almost all components independently of attack aspects. The second reason is that the individual component when described in the Swedish target description is said to have the same presented area in all directions.

The size of the fragment is important to the penetration capability and for some components, such as fuel cells, also to the hole created by the fragment at impact. The importance of the fragment hole size to the aircraft fuel system is noted by combining Pi Terms 5 and 7 which together provide a measure of fuel loss rate. The importance of fragment size in gaging damage to all the aircraft systems is obtained by combining Pi Terms 4, 8, and 9, which together provide a measure of total systems damage.

Pi terms are also used to identify the characteristic of the target. Term 6 will give the presented area of the target compared to the total area of components. Terms 7 and 10 give the importance of the fuel system respectively all other components to a specific target.

6.3 SIMILITUDE MODELING

If the Swedish program LMP-3 is used to calculate the kill probabilities of fragments hitting and spreading evenly over the whole aircraft, the data will plot as illustrated in Figure 27. The kill probability will reach a maximum which is not possible to increase by increasing the striking velocity. If the program had considered fragment breakup, the probability would have dropped after a maximum was reached. This P_{max} is a function of target

Table 7. List of Pi Terms

	Pi Term	Significance
(1)	P	Probability of attrition kill
(2)	$n\left(\frac{M - M_F}{\rho_m}\right)^{2/3}$	Measure of the number of fragment impacts upon the aircraft systems other than the fuel system.
(3)	$n\left(\frac{M_{FR}}{\rho_f}\right)^{2/3}$	Measure of the number of fragment impacts upon the aircraft fuel system.
(4)	$\frac{d}{\left(\frac{M - M_F}{\rho_m} + \frac{M_{FR}}{\rho_f}\right)^{1/3}}$	Measure of the geometric similarity of the fragment to all aircraft systems, based upon characteristic lengths.
(5)	$\frac{D}{V^{2/3}}$	Measure of the geometric similarity of the fragment to the total aircraft, based upon characteristic areas.
(6)	$\frac{A}{\left(\frac{M - M_F}{\rho_m} + \frac{M_{FR}}{\rho_f}\right)^{2/3}}$	Measure of the geometric similarity of the total aircraft to the critical systems of that aircraft, based upon characteristic areas.
(7)	$\left(\frac{M_F/\rho_f}{V}\right)$	Measure of the geometric similarity of the fuel system to the total aircraft, based upon characteristic volumes.
(8)	$\left(\frac{\rho_p}{\rho_m}\right)$	Relates penetrator and target densities for non-fuel systems.
(9)	$\left(\frac{\rho_p V_o^2}{S_m}\right)$	Relates penetrator kinetic energy to aircraft structure/skin strain energy.
(10)	$\left(\frac{W - M_F}{M}\right)$	Relates the mass of all aircraft non-fuel systems to the total aircraft.
(11)	$\left(h_o/d\right)$	Relates the average aircraft skin resistance to penetration to a characteristic penetrator dimension.

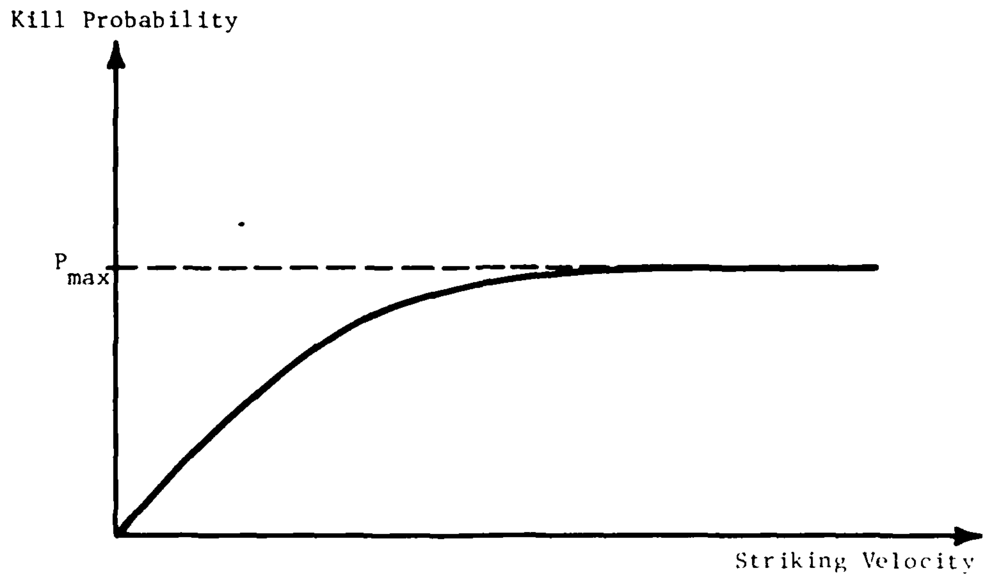

Figure 27. Kill Probability vs Striking Velocity for LMP-3

parameters as well as size and number of fragments. An exponential function can be used to give P_{max}, and as the size of the fragment is more important to damage of the fuel system than to the rest of the components, this system is treated separately. According to the pi terms defined, an assumption for a P_{max} function would be:

$$P_{max} = 1 - e^{-\bar{X}_{max}}$$

$$\bar{X}_{max} = C_1 \; n\left(\frac{M-M_F}{\rho_m}\right)^{2/3} \cdot \frac{M-M_F}{M} + C_2 \; n\left(\frac{M_{FR}}{\rho_f}\right)^{2/3} \frac{D}{V^{2/3}} \cdot \frac{M_F/\rho_f}{V} \qquad (14)$$

where C_1 and C_2 are empirical constants. The first term provides a measure of the vulnerability of the operational systems other than the fuel system. The second term provides a measure of the vulnerability of the fuel system and is related to the rate of fuel loss.

The importance of the fuel system to a target is given by the volume rather than the mass similarity because the size of the aircraft is also important to the fuel consumption.

To define a model for the kill probability it is also important to know how fast this maximum kill probability will be reached. This would be a function of how many of the critical components will be damaged by fragments. The number of components damaged depends on the fragments' penetration capability. From Reference [20], the ballistic limit for low striking velocities and compact fragments ($\ell/d = 1$) is given by:

$$h/d = C_3 \left[\left(\frac{\rho_p}{\rho_m}\right)^{1/2} \left(\frac{\rho_p V_o^2}{S_m}\right)^{1/2} - h_o/d \right] \qquad (15)$$

where h is some kind of an effective thickness. Compared to Reference [20], this expression is reduced with h_o/d corresponding to the thickness of the skin.

The ratio of the number of damaged components to the total number of components can be given by:

$$\bar{Z} = C_4 \frac{A}{\left(\frac{M-M_E}{\rho_m} + \frac{M_{FR}}{\rho_f}\right)^{2/3}} \cdot \frac{h}{d} \cdot \frac{d}{\left(\frac{M-M_F}{\rho_m} + \frac{M_{FR}}{\rho_f}\right)^{1/3}} = \tag{16}$$

$$= C_4 \cdot \left(\frac{A \cdot h}{\frac{M-M_F}{\rho_m} + \frac{M_{FR}}{\rho_f}}\right)$$

The volume containing fragments is A·h. For high fragment velocities, this ratio should approach unity. Use of a hyperbolic tangent function would provide a limit to this effect. Combining this term with the two previous ones will give as an equation for the kill probability:

$$P = 1 - e^{-\bar{X}_{max} \cdot \tanh \bar{Z}}$$

$$\bar{X}_{max} = C_1 n \left(\frac{M-M_F}{\rho_m}\right)^{2/3} \frac{M-M_F}{M} + C_2 n \left(\frac{M_{FR}}{\rho_f}\right)^{2/3} \frac{D}{V^{2/3}} \cdot \frac{M_F/\rho_f}{V} \tag{17}$$

$$\bar{Z} = C_5 \frac{A \cdot \left[\left(\frac{\rho_p}{\rho_m}\right)^{1/2} \left(\frac{\rho_p V_o^2}{S_m}\right)^{1/2} \cdot d - h_o\right]}{\frac{M-M_F}{\rho_m} + \frac{M_{FR}}{\rho_f}}$$

This third term, $\bar{Z}$, provides a multiplier which will increase total aircraft vulnerability as a function of fragment impact velocity until that velocity is reached at which no additional damage is obtained with further increase in velocity.

The results from the Swedish computer program are plotted in Figure 28 and used to determine the values of the constants for this equation. The data used are given in Table 8 and the values of the constants are:

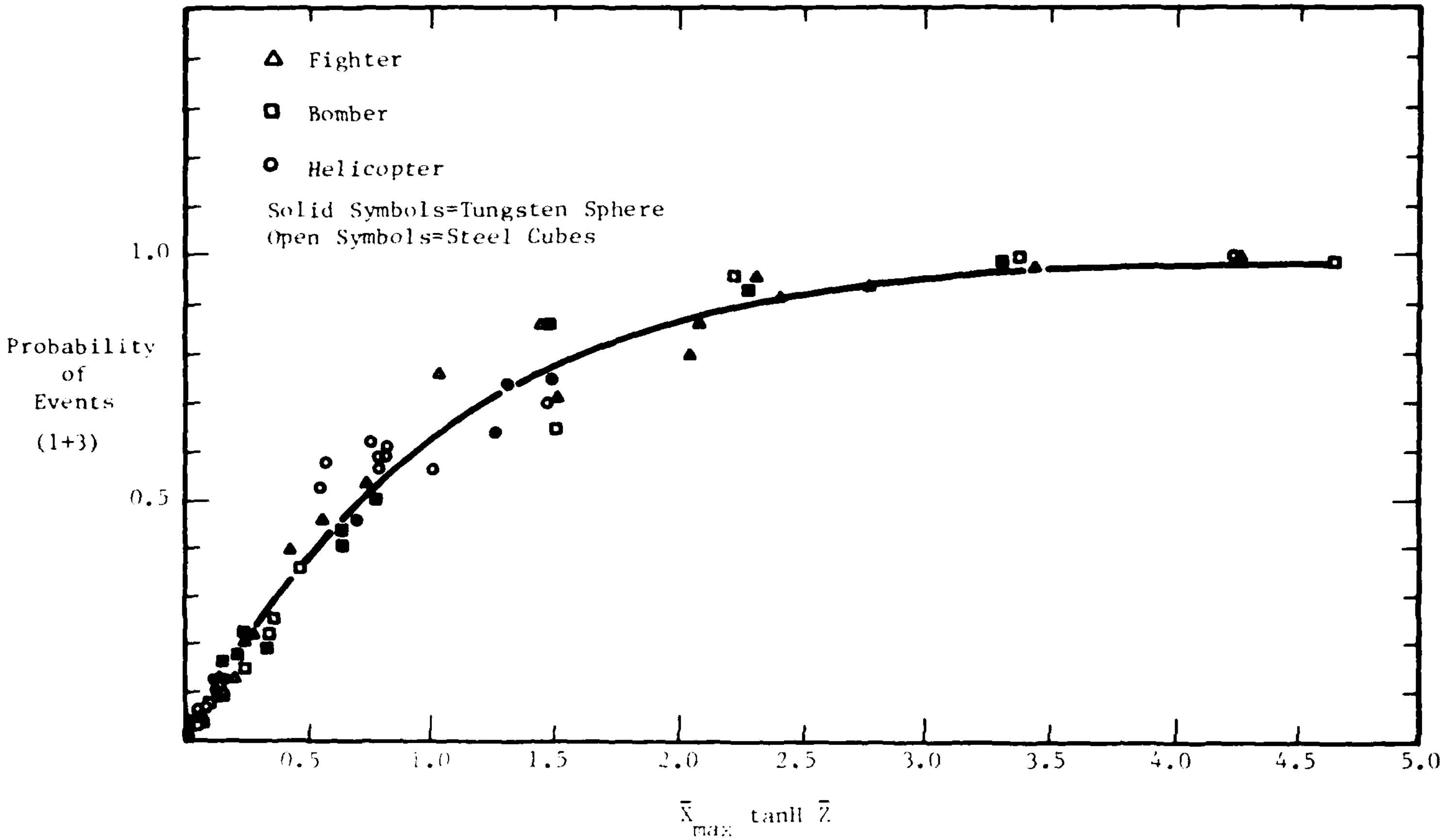

Figure 28. Aircraft Vulnerability Predictor using Results of Swedish Computer Program LMP-3.

Table 8. Data Used in Swedish Computer Program

Symbol	Parameter	Value
n	Number of fragments per unit area	0.1, 1, 10 frag/m^2
V_o	Striking velocity	1000, 2000, 3000 m/s
D	Presented area of fragment	Steel Cube: 1×10^{-4} m^2 Tungsten Sphere: 0.071×10^{-4} m^2
ρ_p	Fragment material density	Steel Cube: 7800 kg/m^3 Tungsten Sphere: 17200 kg/m^3
d	Fragment diameter	Steel Cube 1×10^{-2} m Tungsten Sphere: 0.3×10^{-2} m
A M M_F V	From Jane's All the World's Aircraft for the fighter, bomber and helicopter; side view and bottom view	
M_{FR}	Mass of remaining fuel	Fighter: 60% Bomber: 40% Helicopter: 30%
ρ_f	Fuel density	700 kg/m^3
S_m	Shear strength of target	3×10^8 N/m^2
P	Kill probability	Output from LMP-3
ρ_m	Average density of component material	3000 kg/m^2
h_o	Average skin thickness of the target	~ 3 mm dural

$C_1 = 0.25$

$C_2 = 125 \times 10^4$

$C_5 = 8.0 \times 10^{-3}$

The thickness of the skin h_o is approximately 3 mm aluminum and for the bomber, the presented area of the side view has been reduced by 50%, as this is a twin-engine aircraft and, therefore, has much redundancy. For the helicopter, the presented area of the rotor blades is not included.

The equation gives a good agreement with the data and should be useful for estimating kill probability. However, the equation is limited to effect of fragments which are assumed to be evenly spread over the whole target. The model seems to cover the variations of fragment parameters quite well. Some tests for higher and lower striking velocities have been made and the agreement is still good. The scatter might increase a little for the lower velocities. The type of fragment (size, material, shape) might need some further investigation, since in this example only two types of fragments have been used and for those all three parameters have been changed. However, the influence on the penetration capability should be easily calculated. More uncertain is the influence of the fragment size on $\bar{X}_{max}$.

How well the model can be used for different kinds of targets is questionable, but the example here with the fighter, bomber and helicopter seems promising. However, these targets are all old aerial targets without any extra armoring and do not have much redundancy. However, increasing the overall skin thickness and decreasing the presented area of the target may solve some problems. Some more calculations against other targets would be necessary. Hopefully, this will be done, making it possible to improve and increase the understanding of the model and determine the limitation of the model.

Equation 17, fitted to the data presented on Figure 28, provides the capability to make a quick estimate of the attrition vulnerability of an aircraft at a given attack aspect to a fragmenting warhead. This estimate would be a measure of aircraft vulnerability as predicted by LMP-3. Since the data used to develop the three empirical constants used in the equation were from assessments of a fighter, a bomber, and a helicopter, these constants are appropriate for most aerial targets. Note that the independent

parameters used (given in Table 6) are all simple enough that most of them are available in Jane's All the World's Aircraft. This equation is based upon assessments made using LMP-3, but similar equations could be developed using U.S. Aerial Target Vulnerability assessment programs, with a greater variety of attack munitions and aerial targets. Such as equation would be extremely valuable to the U.S. ATV assessment community.

6.4 EXAMPLE OF USE OF LMP-3 BASED SIMILITUDE MODEL QUICK-ANALYSIS TOOL

The model can be used to estimate the effect of a specified threat against a target. To demonstrate use of the model, the attrition vulnerability of MiG-21, MiG-23 and MiG-25 aircraft to impacting fragments has been estimated. The fragments assumed are 2.0 or 7.8 gram steel cubes with a striking velocity of 1000 m/s (velocity relative to target) and fragment densities of 0.1 and 1 fragment/m^2. The data needed for the targets have been found in Jane's All the World's Aircraft or estimated from drawings and data given there. A review of target data used is in Table 9. All aircraft are assumed to have 50 perc. . of their total fuel remaining at the moment of attack.

These data are then used to calculate $\overline{X}_{max}$ tanh $\overline{Z}$ and the kill probability P is given by:

$$P = 1 - e^{-\overline{X}_{max} \tanh \overline{Z}}$$

The results for the 2.0 gram fragments are shown in Table 10 and the 7.8 gram fragments in Table 11. The kill probabilities here are, of course, the Swedish attrition kill (Event 1 + Event 3) as the model is based on LMP-3 results. These results can be equated roughly to U.S. "B" kill. As target descriptions of these aircraft are not available for use with the Swedish model LMP-3, there are no computer results available to compare with these predictions.

Table 9. Data Used for Example

MiG-21	Volume	20 m^3
	Total mass	9000 kg
	Mass of fuel	1800 kg
	Remaining fuel	900 kg
	Presented area from below	37 m^2
	Presented area from side	27 m^2
MiG-23	Volume	33 m^3
	Total Mass	18000 kg
	Mass of fuel	3800 kg
	Remaining fuel	1900 kg
	Presented area from below	50 m^2
	Presented area from side	29 m^2
MiG-25	Volume	66 m^3
	Total Mass	30000 kg
	Mass of fuel	14000 kg
	Remaining fuel	7000 kg
	Presented area from below	75 m^2
	Presented area from side	39 m^2

Table 10. 2.0 Gram Steel Cubes Striking with a Velocity of 1000 m/s and a Density of 1 Fragment/m^2

Target	Striking Direction	Probability of Events (1+3) (Attrition Kill)
MiG-21	Below	0.38
	Side	0.30
MiG-23	Below	0.40
	Side	0.26
MiG-25	Below	0.57
	Side	0.20

Table 11. 7.8 Gram Steel Cubes Striking with a Velocity of 1000 m/s from Below

	Probability of Events (1+3) (Attrition Kill)	
Target	1 Fragment/m^2	0.1 Fragment/m^2
MiG-21	0.81	0.15
MiG-23	0.84	0.17
MiG-25	0.97	0.29

7.0 SUMMARY AND CONCLUSIONS

7.1 COMPARISON OF MATHEMATICAL MODELS

The three largest differences between the mathematical models are structural kill (not treated in the Swedish model), the calculations of fragment penetration capability, and the definition and use of damage criteria. As the structural kill is not treated in the Swedish model, this model is not capable of handling warheads specially designed to cause structural kill.

The fragment penetration model which is used in the Swedish computer program makes it possible to simplify the target descriptions and the calculations. However, the accuracy of this method can be questioned and work has just started in Sweden to improve the method and increase the test data base.

The U.S. damage criteria are defined for aircraft components and the Swedish for aircraft functional systems. This gives the U.S. model the possibility of relating component damages to fragment size and velocity, and the Swedish model of relating system malfunctioning to pilot's reaction.

Both countries also have many problems in common, such as time-consuming target descriptions, the need for alternate methods and compact equations which cover a wide range of parameters, and ways to handle complex physical phenomena.

The time needed to complete a target description is said to be almost the same in both countries. However, when the Swedish target description is complete it is also ready to be used against any warhead in the computer program which will calculate the kill probabilities. After the U.S. description is made three different computer programs must be run before the same results kill probabilities are reached, and the resultant tables of vulnerable area are applicable only to the threat input.

In both countries there is a need for approximate methods that can be used to make an early estimation in a short time. This is valid for the whole problem as well as portions of the problem. The estimations could for example concern the effect of a warhead against a certain aircraft which is not known in all its details, or a fragment's penetration capability against a material for which no test data are available.

Physical processes such as fuel fire, hydrodynamic ram and spall are best treated by the U.S. damage criteria which are probably more amenable to handling these problems.

7.2 COMPARISON OF COMPUTER RUNS

A complete comparison is possible for only one target, the bomber. Some of the differences in assessment results (Figure 15 and 19) could result from differences in details of the target descriptions; these details were not available for this study. The differences in projectile effects could be affected by the treatment of a tungsten fragment since the U.S. table of vulnerable area used was for steel fragments the minimum size of which was one gram. The results are useful as an indication of relative results from the two models and can be used to compare future Swedish and U.S. aerial target vulnerability assessments. The results are those which in each country would have been used in an evaluation of a weapon system or a warhead design. The conclusions might have been quite different if they were based on the Swedish or the U.S. results. The Swedish probabilities are generally higher.

7.3 SIMILITUDE MODEL

The agreement between the Swedish computer results and the model are very good and it should be possible to develop similar models for other types of targets and/or threats. However, in order not to be limited to threats covering the whole target it might be necessary to develop models for target systems such as engine, fuel cells, cabin, or avionics.

7.4 RECOMMENDATIONS

There is no compelling reason for either country to use the other's model. Neither model can be proven to be superior to the other. Furthermore, there would be a dual initial cost in creating new target descriptions for use in the other country's model as these could not be transferred directly.

Some portions of the models which are better solved in the other country might be worth trying to implement. Examples are better damage criteria for the components transferred to the Swedish model, and inclusion of the pilot's behavior in the U.S. model. However, the models are so integrated that such extension might be very costly and cause much more complex models.

In order to provide a better correlation between the Swedish and U.S. methodologies, in both countries, each should make a target description of the same unclassified aircraft, using a common set of aircraft descriptive data. Then it would be possible to compare the methods in all their details and to identify the sources of differences in the computed vulnerability assessments.

The kill categories used should be reviewed by analysts of each country and, hopefully, both countries could benefit from this exposure to the others techniques.

Both countries have a need to make more sensitivity analyses of their models. Exchange of those results would benefit both, and perhaps reduce the work which has to be done in each country.

The similitude modeling shows good promise for developing approximate methods, and deserves further efforts.

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APPENDIX A

TARGET MODEL PREPARATION FOR

FASTGEN/SHOTGEN

(Extracted from ASD-TR-77-24, FASTGEN II Target Description Computer Program by George E. Belote and James D. Severance, with permission from ASD/XROT, AFSC, USAF.)

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TARGET MODEL PREPARATION

Vulnerable area calculation computer programs, such as VAREA or COVART, require target line-of-sight description input of sufficient detail and completeness to ballistically represent the target from any attack aspect considered. The FASTGEN II computer program provides this description by developing item-by-item listings of target components and air spaces encountered along a large number of uniformly distributed parallel rays emanating from a specific direction and passing completely through the target.

Prerequisite to FASTGEN II execution is the requirement to prepare realistic machine-readable geometric descriptions, or models, of all target components significant for vulnerability analyses. A FASTGEN II geometric model is based on the fact that the surfaces, flat or curved, exterior or interior, of the individual components of the target may be approximated by a series of adjacent triangles or cone, cylinder, sphere, and rod segments. This model preparation process is intricate and must be accomplished according to inherent FASTGEN II logical regulations and with explicit knowledge of FASTGEN II logic limitations. Ignorance of how FASTGEN II processes target description data can lead to inaccurate target models which inadequately portray target vulnerability. Target model preparation should, therefore, be carefully accomplished in accordance with known model applications. Seven major steps in the geometric model preparation process are as follows:

- Definition of Target Model Purpose
- Compilation of Target Component Code List
- Acquisition of Detailed Orthographic Design Drawings
- Development of Component Sketches
- Establishment of Component Coordinates
- Creation of Target Model File
- Validation of Target Model.

The purpose of this section is to describe specific model preparation procedures recommended during each of the

above steps and to guide future input data preparation processes. Where applicable, frequently encountered pitfalls are discussed. In addition, proven shortcut model preparation methods are described. The magnitude of potential component configurations limits discussions in this section to basic and/or general aspects of model preparation. Combination of these basic operations is left to the discretion of each target description preparer.

1. TARGET MODEL PURPOSE

An initial requirement of the target model preparation process is the exact definition of the target model purpose (i.e., expected application in subsequent vulnerability program computations). Target models are normally prepared to depict the vulnerability of components located within military vehicles which, when damaged, result in some expected level of vehicle incapacitation. This requires the description of both prescribed vulnerable components and also significant shielding components that lessen the effect of damage mechanisms striking exterior vehicle surfaces. Target model preparation efforts are significantly reduced if only the external target surfaces are required (i.e., if only the probability of target hit is requred).

When internal vulnerable component modeling is required, the type of kill being analyzed directly influences the amount and type of components to be modeled. Three commonly analyzed kill levels for aircraft are:

- K-Kill: Damage causing the target to fall out of control within 30 seconds
- A-Kill: Damage causing the target to fall out of control within 5 minutes
- Mission: Damage resulting in loss of capability to complete designated mission.

The type(s) of damage mechanism(s) expected to be evaluated against the target model should also be established. FASTGEN II has the capability to simulate parallel straight-line trajectories of bullets, fragments, non-fragmenting projectiles, lasers, and, generally, any mechanism that can be simulated by a zero cross-section ray. Although the expected damage mechanism does not directly enter into target model processing, it does influence model preparation decisions for small cross-section components.

Concise development of expected model purposes permits establishment of realistic model preparation effort estimates. Such estimates are not absolute, but are useful for the allotment of fixed manpower levels to known objectives. Model preparation effort estimates for three typical targets are given below:

TARGET	FASTGEN II MODEL PREPARATION*
SRAM Missile	1.5 Man Months
F-4 Fighter	6 Man Months
B-1 Bomber	10 Man Months

* Estimates based on experienced model preparer and utilization of similar components of other models.

These estimates are for targets which require the description of internal vulnerable components in the detail required *for a mission abort assessment* and could be halved if only exterior surface modeling was required. These estimates assume that all source information required to prepare model descriptions is readily available.

2. TARGET COMPONENT CODE LIST

The level of target description detail required governs the number of target components which require modeling. Target component code lists reflect this level of required detail and serve to numerically organize component descriptions into their respective subsystems.

FASTGEN II requires that each component being modeled be identified by a four-digit component code number. Although any component code assignment system can be used, the following standard code categories have been established for previous assessments of ground vehicles and aircraft.

GROUND VEHICLES

STANDARD COMPONENT CODES	COMPONENT FUNCTIONAL CATEGORY
0001 through 0999	Body
1001 through 1999	Engine and Accessories
2001 through 2999	Crew
3001 through 3999	Personnel or Cargo
4001 through 4999	Fuel System
5001 through 5999	Ammunition
6001 through 6999	Armament
7001 through 7999	Power Train and Suspension System
8001 through 8999	Electrical System
9001 through 9999	Miscellaneous

AIRCRAFT

STANDARD COMPONENT CODES	COMPONENT FUNCTIONAL CATEGORY
0001 through 0999	Skin and Bulkheads
1001 through 1999	Power Plant
2001 through 2999	Crew
3001 through 3999	Flight Control System
4001 through 4999	Fuel System
5001 through 5999	Ammunition Including Bombs
6001 through 6999	Armament
7001 through 7999	Structural Members
8001 through 8999	Electrical System
9001 through 9999	Miscellaneous

Specific component code numbers within functional categories (i.e., the last three digits) are dependent on modeling requirements applied to the specific target. Each component must be composed of only one material type to allow proper component vulnerable intercept treatment in subsequent vulnerability programs, such as VAREA or COVART.

Component code list entries can be effectively developed from target lethal criteria analyses. These analyses, referred to as failure modes, effects, and criticality analyses (FMECA), include four major steps:

- Identification of each major target component function with respect to system and vehicle operation
- Determination of potential failure modes resulting from exposure to threat
- Determination of effects of these failure modes on system and vehicle performance
- Assignment of component kill classification defining the criticality of the component and failure mode.

FMECAs are conducted using target physical characteristics, properties, and locations of critical and shielding components.

A typical component code list is contained in Table 2. Component number sequencing within major categories illustrates how component codes can be logically and orderly assigned. Shielding components are derived from target assembly drawings and technical orders. The final component code list of necessity evolves during the entire model preparation process.

3. DETAILED ORTHOGRAPHIC DESIGN DRAWINGS

The most important step in obtaining the basic input data for the FASTGEN II description of any target is the acquisition or preparation of standard orthographic drawings, including principal dimensions and all necessary sectional and auxiliary views of the target (see Figure 1). Sources for these drawings include vendor facilities for actual production drawings, technical publications including FMECAs,

TABLE 1. SAMPLE MISSILE COMPONENT CODE LIST

COMPONENT NUMBER	COMPONENT NAME
0001	Nose section
0002	Skin, Stations 30.0 to 46.2 - bottom
0003	Skin, Stations 30.0 to 46.2 - top
0004	Skin, Stations 46.2 to 66.2 - bottom
0005	Skin, Stations 46.2 to 66.2 - top
0006	Skin, Stations 66.2 to 81.75 - bottom
0007	Skin, Stations 66.2 to 81.75 - top
0008	Skin, Stations 81.75 to 95.2 - bottom
0009	Skin, Stations 81.75 to 95.2 - top
0010	Skin, Stations 95.2 to 105.7 - bottom
0011	Skin, Stations 95.2 to 105.7 - top
0012	Skin, Stations 105.7 to 124.2 - bottom
0013	Skin, Stations 105.7 to 124.2 - top
0014	Skin, Stations 124.2 to 145.48 - bottom
0015	Skin, Stations 124.2 to 145.48 - top
0016	Fairing, air intake
0017	Skin, Stations 145.48 to 155.07 - bottom
0018	Skin, Stations 145.48 to 159.8 - top
0019	Skin, Stations 155.07 to 159.8 - bottom
0020	Skin, Stations 159.8 to 178.0 - bottom
0021	Skin, Stations 159.8 to 178.0 - top
0023	Air intake, outer surface
0024	Phantom armor, air intake
1001	Housing, inlet
1002	Spinner, compressor
1003	Blades/Stators, axial compressor - low pressure
1004	Discs, axial compressor - low pressure
1005	Housing, axial compressor - high pressure
1006	Blades/Stators, axial compressor - high pressure
1007	Discs, axial compressor - high pressure
1008	Air duct, axial compressor
1009	Housing, radial compressor
1010	Rotor, radial compressor
1011	Air duct, radial compressor
1012	Combustion chamber
1013	Housing, turbine
1014	Blades/Stators, turbine - first stage
1015	Disc, turbine - first stage
1016	Blades/Stators, turbine - second stage
1017	Disc, turbine - second stage
1018	Blades/Stators, turbine - third stage
1019	Disc, turbine - third stage
1020	Drive shaft, low pressure

TABLE 1. SAMPLE MISSILE COMPONENT CODE LIST (CONTINUED)

COMPONENT NUMBER	COMPONENT NAME
1021	Drive shaft, high pressure
1022	Bearing, low pressure shaft - front
1023	Bearing, low pressure shaft - rear
1024	Bearing, high pressure shaft - front
1025	Bearing, high pressure shaft - rear
1026	Housing, bypass - inner
1027	Housing, bypass - outer
1028	Exhaust nozzle
1029	Tailcone
1031	Oxygen tank
1032	Oxygen tank connector
1033	Engine starter cartridge
1041	Generator
1042	Alternator
1043	Sensor, inlet temperature
1051	Power setting actuator
1052	Fuel control unit
1053	Fuel filter
1054	Fuel line, fuel control to oil cooler
1055	Fuel line, oil cooler to burner
1061	Oil unit (pump, filter, reservoir)
1062	Oil cooler
1071	Accessory drive
1081	Engine mount - left
1082	Engine mount - right
1083	Engine mount - lower
4001	Boost pump, fuel
4002	Sump pump, jet
4003	Fuel line
4005	Fuel, Stations 30.0 to 66.2
4006	Fuel, Stations 66.2 to 95.2
4007	Fuel, Stations 95.2 to 105.7
4008	Fuel, Stations 105.7 to 145.48
4009	Fuel vapor, Stations 81.75 to 124.2
4010	Fuel vapor, Stations 124.2 to 145.48
7001	Fitting, forward clevis
7002	Fitting, aft clevis
7005	Bulkhead, Station 30.0
7006	Tank top, Stations 30.0 to 66.2
7007	Frame, Station 36.2
7008	Frame, Station 46.2
7009	Frame, Station 56.2

TABLE 1. SAMPLE MISSILE COMPONENT CODE LIST (CONTINUED)

COMPONENT NUMBER	COMPONENT NAME
7010	Frame, Station 66.2
7011	Tank top, Stations 66.2 to 81.75
7012	Frame, Station 74.2
7013	Frame, Station 81.75
7014	Frame, Station 87.1
7015	Frame, Station 95.2
7016	Frame, mount, forward
7017	Frame, Station 102.4
7018	Frame, Station 105.7
7019	Frame, Station 115.2
7020	Frame, Station 124.2
7021	Frame, mount, aft
7022	Tank top, Stations 124.2 to 145.48
7023	Frame, Station 131.1
7024	Frame, Station 138.1
7025	Frame, Station 155.07
7026	Longeron, Stations 145.48 to 155.07
7027	Longeron, Stations 155.07 to 165.2
7028	Frame, Station 165.2
7029	Frame, Station 169.5
7030	Frame, Station 172.8
7031	Tank top, Stations 81.75 to 124.2
8001	Radar altimeter, electronics
8002	Radar altimeter, antenna
8003	Air data unit
8004	Bulk memory element
8005	Flight control electronics
8006	Inertial navigation element
8008	Transformer rectifier
8009	Rate gyro
8010	Connector, umbilical
8011	Switch, separation
8012	Actuator control, elevon
8013	Battery, thermal - left
8014	Battery, thermal - right
8015	Actuators, elevon
8020	Actuator, fin deploy
8021	Actuator, elevon deploy
8022	Actuator, wing deploy
9001	Payload envelope
9002	Heat exchanger
9010	Wing, bottom surface - left

TABLE 1. SAMPLE MISSILE COMPONENT CODE LIST (CONCLUDED)

COMPONENT NUMBER	COMPONENT NAME
9011	Wing, top surface - left
9012	Wing, bottom surface - right
9013	Wing, top surface - right
9014	Elevon, lower surface - left
9015	Elevon, upper surface - left
9016	Elevon, lower surface - right
9017	Elevon, upper surface - right
9018	Fin, vertical
9019	Wing, ends - left
9020	Wing, ends - right
9021	Elevon, ends - left
9022	Elevon, ends - right
9024	Air intake, inner surface

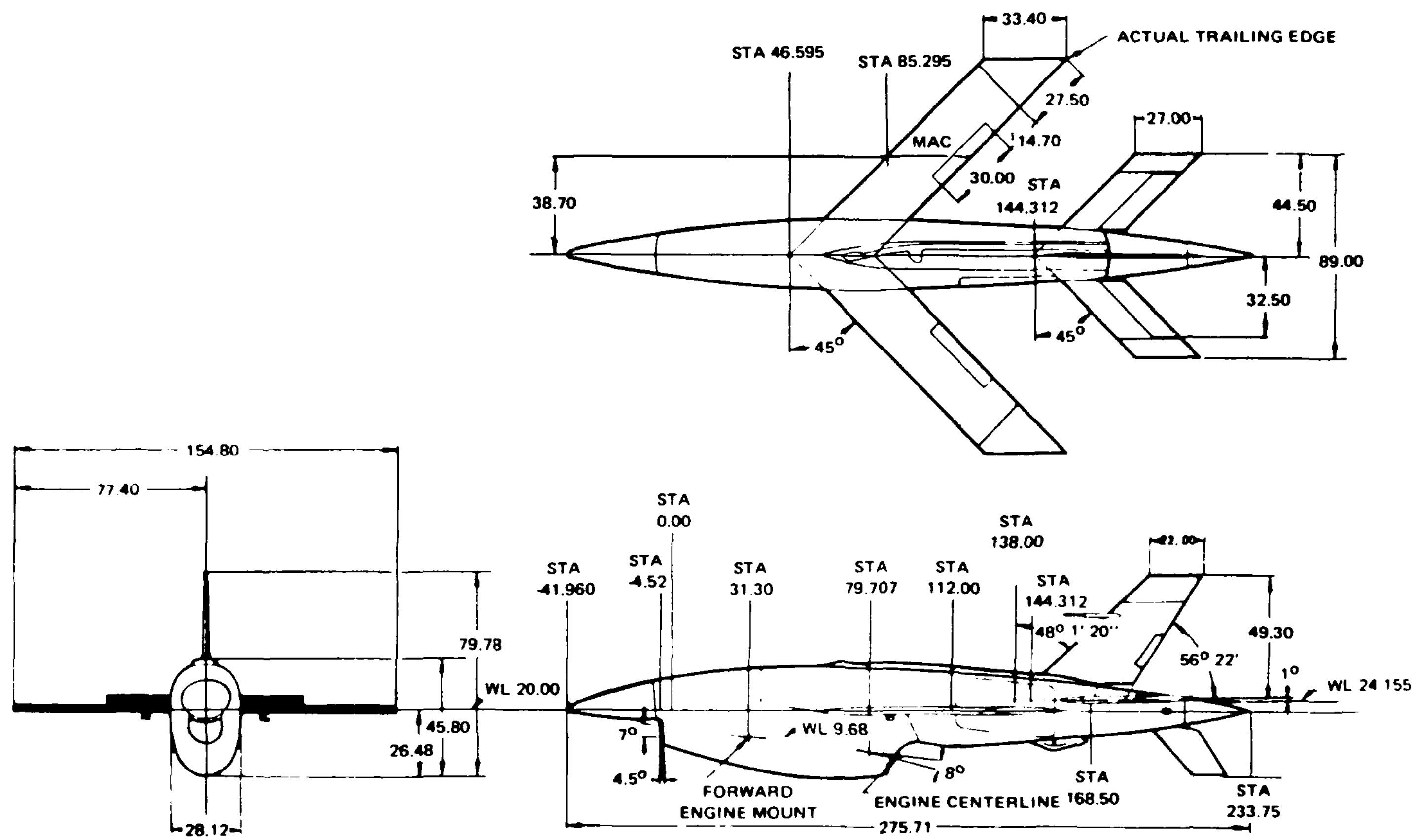

Figure 1. Principal Dimensions of BQM-34A

photographs, verbal instructions, and measurements of the actual target. Acquisition of an inboard profile is necessary to permit the determination of exact locations and geometries for internal components (see Figure 2).

Availability of orthographic design drawings for targets depends to a large extent on the vehicle's production status. Acquisition of all design drawings is not necessary or recommended. Rather, those acquired should be selected from an examination of established critical or vulnerable components and their associated significant shielding elements.

The direct examination and measurement of an actual target is frequently required to complete orthographic drawing details. If an exact target is not available, earlier or later versions are often identical or at least similar in areas requiring further definition. Field measurements of actual targets must be carefully conducted to ensure accurate integration with other documented information.

The final set of target orthographic information is derived from a variety of source material. Model preparers should list the information extracted from each source so that final target description details can be adequately referenced. Special care should be taken to document any preparer assumptions concerning vulnerable component location, shielding structure thickness, etc. This list will greatly facilitate later updates to the target model and will also document the assumptions built into the composite target model description.

4. TARGET COMPONENT SKETCHES

This target model preparation step involves the preparation of isometric sketches of target components compiled in the Target Component Code List. All components should be consistently drawn as if the viewer were looking at the component from a point in space in front of, and above, its left front corner. Component circles which lie in planes that are perpendicular to the three coordinate axes may be drawn with an isometric template. No attempt should be made to sketch the component to scale. Instead, the relative shape should be maintained together with a minimum of interference between non-related component edge points. Figure 3 illustrates a poor and a good sketch of the same component. The sketch labeled good provides more space for labeling

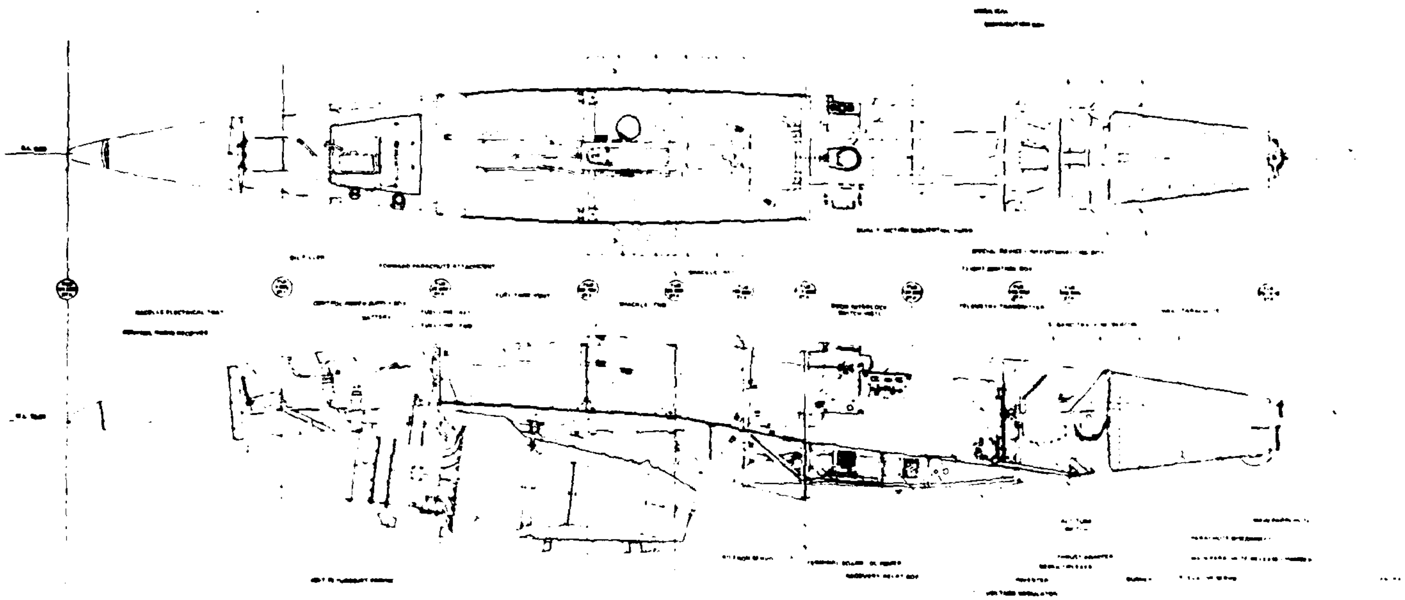

Figure 2. Inboard Profile of BQM-34A

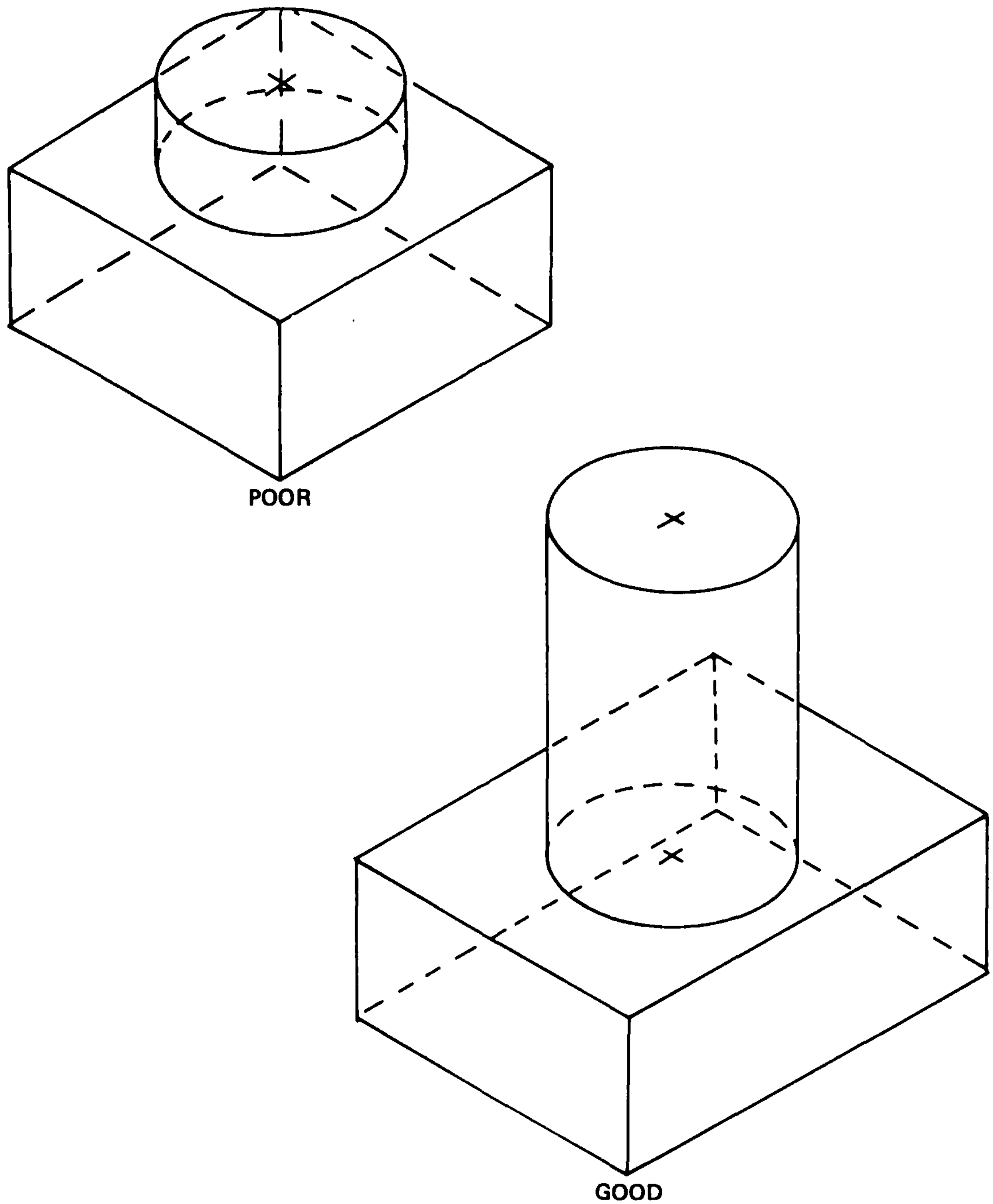

Figure 3. Poor and Good Component Sketches

triangle points if the component is coded as a triangle type. It is advantageous to adopt a standard worksheet format for sketch preparation.

5. TARGET MODEL COORDINATES

This step requires the completion of three separate but interrelated tasks:

- Location of an overall target coordinate system
- Selection of component modeling methodology
- Determination of component coordinate values.

General procedures for accomplishing each task are discussed in the following paragraphs.

a. Target Coordinate System Location

Target components must all be located by appropriate dimensions and the location of the origin is arbitrary. It can be at the approximate geometric center of the target, be coincident with some predominant and easily recognizable feature on the exterior surface of the target, or completely outside the target.

FASTGEN II requires a right-hand Cartesian coordinate system. For aircraft, the target center is normally located along the fuselage longitudinal centerline to take advantage of structural and system symmetry. An origin position along the longitudinal axis is nominally selected to correspond with the fuselage coordinate measurement system and/or with some major structural or system component boundary. For ground vehicles, the origin is normally selected to coincide with the target centroid projected vertically onto the ground plane.

b. Component Modeling Selection

Target model components are often a combination of several separate segments, each with different geometric characteristics. These qualities are defined with geometry

type and mode. FASTGEN II permits the description of each component segment with one of four types; triangles, cones (or cylinders), spheres, or rods. A description mode is associated with these types, except rod-type.

Description with triangles involves approximating component surfaces with adjacent triangular planes and, in general, involves more preparation time, requires more computer run time, and is less accurate than any of the other methods. The preparer is, therefore, advised to select cone (or cylinder), sphere, or rod descriptive techniques whenever possible. Modeling techniques (except for rod) can be mixed within a component.

Components (except rod-type) can be described in either plate or volume mode. Volume mode requires that all exterior surfaces be described. The plate mode is effective when describing relatively thin components having parallel surfaces such as wing skin segments or bulkheads. Although the plate method may be used for components ranging in thickness from 0.01 inch up to and including 0.99 inch, it is generally restricted to components less than 0.50-inch thick. The main advantage of the plate mode over volume mode is that only one surface of the component needs to be approximated and identified. Modes should not be mixed for component segments of the same component.

c. Component Coordinate Values

This task involves the determination of coordinate values for each component segment in accordance with the respective modeling technique selected. Coordinate values should be entered onto component sketches prepared during Step 4.

If the triangular approximation method is selected, component surfaces are defined with adjacent triangular planes, and coordinates are required for each triangle vertex point. There are no established rules for determining the number of triangles required to adequately approximate component surfaces. Major considerations include the degree of surface detail required (especially for contoured surfaces such as wings), and the necessity to enclose all components that are interior to the surface being approximated.

FASTGEN II program logic requires that triangle vertex point data be ordered (i.e., sequenced) such that

any consecutive trio of points uniquely define either a triangle or a straight line (degenerate triangle). To properly arrange the point data, a sketch of each surface to be approximated should be drawn and the sequence of triangle points determined and recorded on the sketch.

Examples of proper vertex point sequencing are contained in Figure 4. Each of the surfaces shown are divided into triangular planes, and each triangle is defined only one time by three points in sequence. In Figure 4 (a), points 2, 3, and 4 and points 3, 4, and 5 define two triangles which completely describe the surface of the quadrilateral. In Figure 4 (b), points 2, 3, and 4; 3, 4, and 5; 4, 5, and 6; 5, 6, and 7; 6, 7, and 8; and points 7, 8, and 9 define the five triangles which describe the entire surface of the polygon. Figure 6 contains examples of improper point sequencing. In Figure 5 (a), Triangle A is described twice, and Triangle B is never described. In Figure 5 (b), Triangle A is described twice. Finally, Figure 5 (c) is sequenced improperly because Triangle A is described twice and Triangle B is not described.

When describing two-dimensional surfaces that are not polygons (i.e., circles, ellipses, and other surfaces bounded by curves), the surfaces are approximated by considering them as polygons with sides which closely follow the perimeter. The level of descriptive detail utilized for these surfaces is, of course, dependent on the number of sides used. Figure 6 shows an example of approximating a circular surface and an example of describing an irregular surface with both straight and curved sides. Proper sequencing numbers are also shown.

The sequencing techniques that must be used in describing the surfaces of flat-sided objects are essentially the same as those used for describing plane surfaces. Figure 7 illustrates one acceptable method for sequencing a flat-sided object. The sequence of points in Figure 7 is chosen so that each surface of the object is described only once. Double points are required for the first and last vertex of each triangle segment so that SHOTGEN target models will be compatible with the FASTGEN II computer program. Note also that double points (17 and 18) are utilized so that the rear surface of the object can be described properly. If point 18 is not used as a double point and instead is located with point 11, then points 16, 17, and 18 will describe a triangle which does not lie on the surface of the object. Point 19

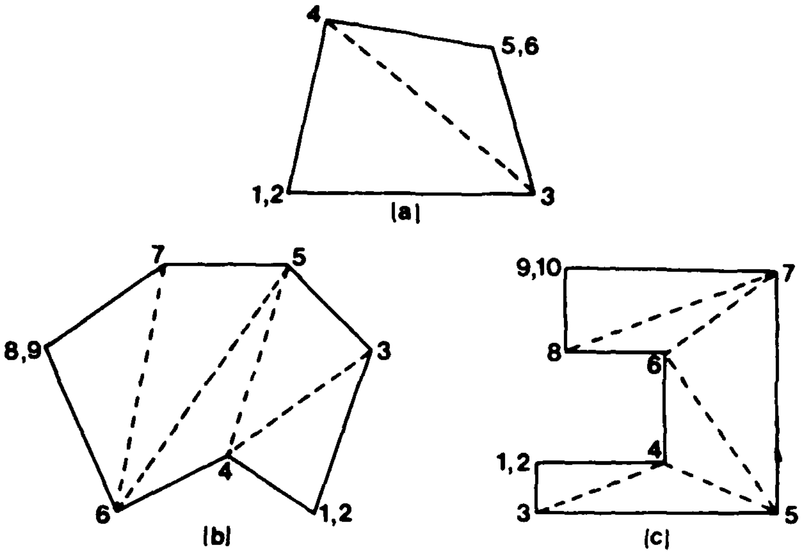

Figure 4 . Proper Sequence of Points for Flat-Sided Surfaces

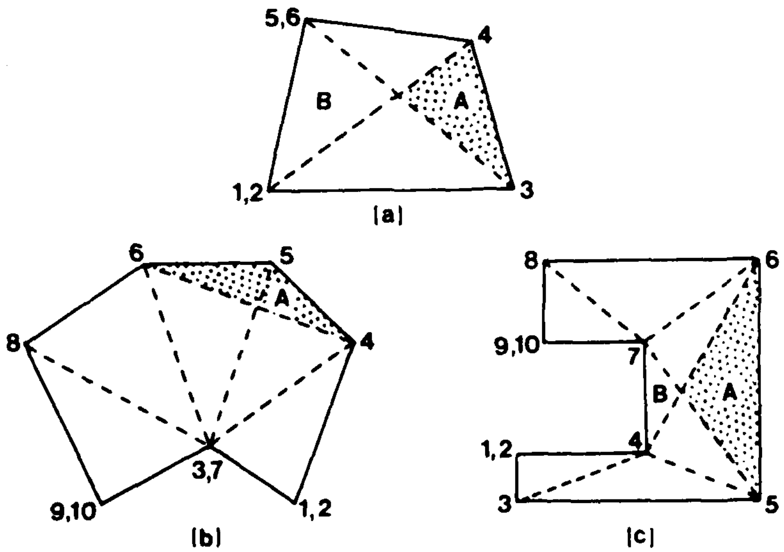

Figure 5 . Improper Sequence of Points for Flat-Sided Surfaces

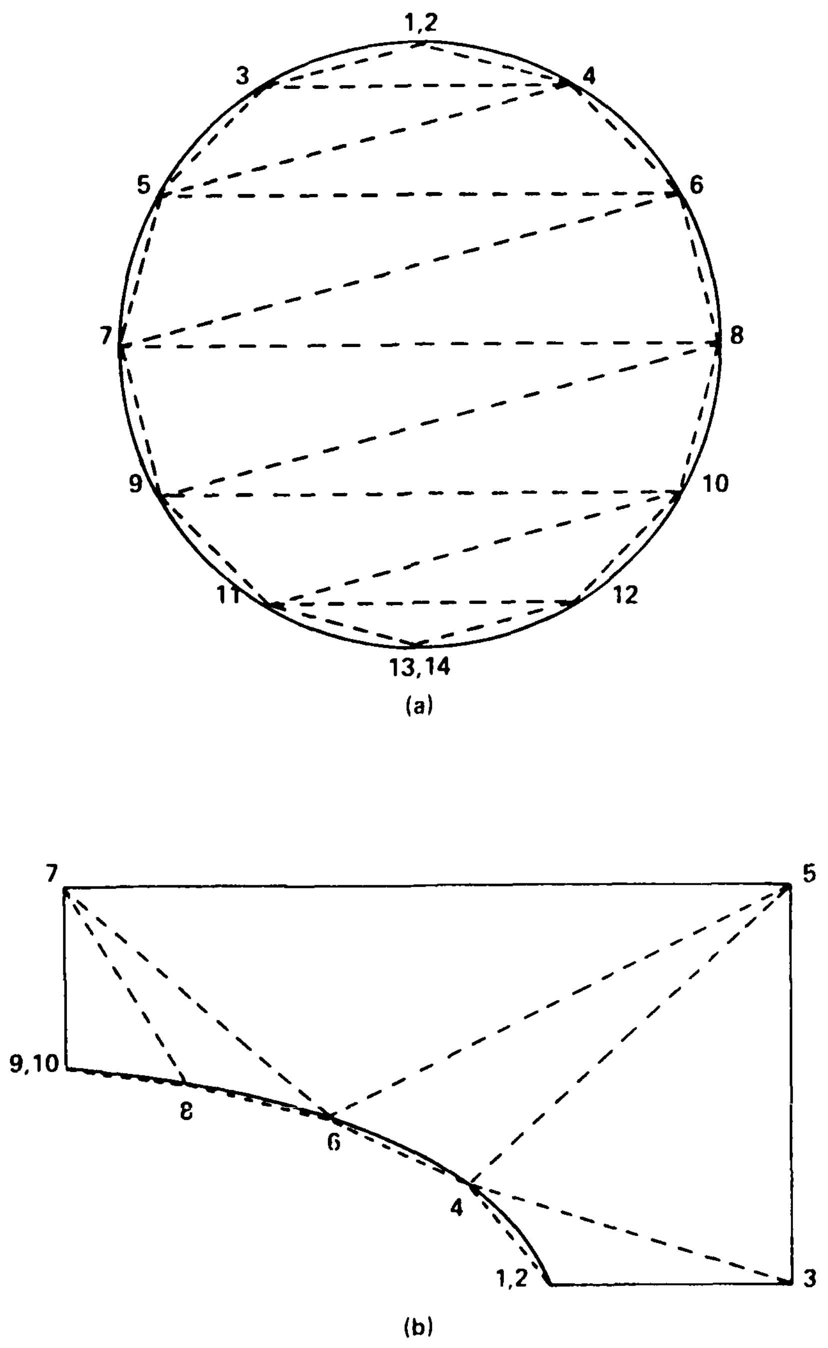

Figure 6. Approximation and Proper Sequencing of Curved Surfaces

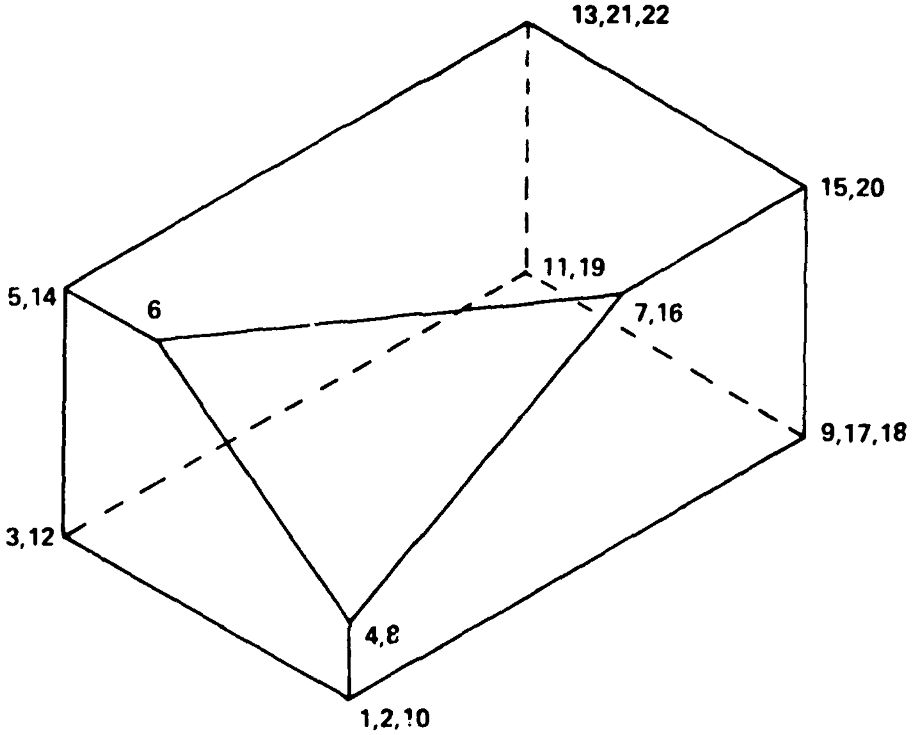

Figure 7. Point Sequencing of a Flat-Sided Object

is then placed so that points 17, 18, and 19 describe a straight line which is the base of the next triangular surface to be described. Also, point 19 can be placed with point 15, and point 20 can be placed with point 11, and the rear surface of the object will be described properly. Figure 7 shows only one of many acceptable methods for sequencing the points of the object. Any method is acceptable so long as it describes the entire surface of the object only one time.

The sequencing techniques that must be used in describing objects with curved or irregular surfaces are essentially the same as those used for describing plane surfaces. Figure 8 shows two typical objects with curved surfaces and acceptable methods for approximating their surfaces. Although the hidden surfaces of the objects are not shown, these surfaces must also be described, if volume mode.

A simplified description method is available to describe cones (or cylinders), spheres, and rods. For truncated cones and cylinders, this method requires the determination of the X-, Y-, and Z-coordinates of each component axis end point and the radius of each end plane. The description for spheres requires only the sphere centroid coordinates and the sphere radius. For components described as rods, only the rod segment end points need be determined.

Cones, cylinders, and spheres can be used to describe either solid and hollow components. Hollow component descriptions can be obtained using the plate mode or a volume subtraction technique. As a general rule, plate mode are only employed when component walls are thin. For cones and cylinders described in plate mode, only the side walls are included; end planes must be described separately.

Volume subtraction involves the description of two bodies, one within the other, and each with the same component number. Volume subtraction is used to describe cylinders and spheres with thick walls and can also be used to describe cylinders and truncated cones with closed ends.

Four examples of simplified methods for describing hollow shapes are contained in Figure 9. Figure 9 (a) is described in plate mode and requires the coordinates of each axis end point, the radius of each end and the normal wall thickness. Figure 9 (b), described in volume mode, requires the description of two cylinders. The first is defined by axis end points 1 and 2, and radii R_1 and R_2, the second by

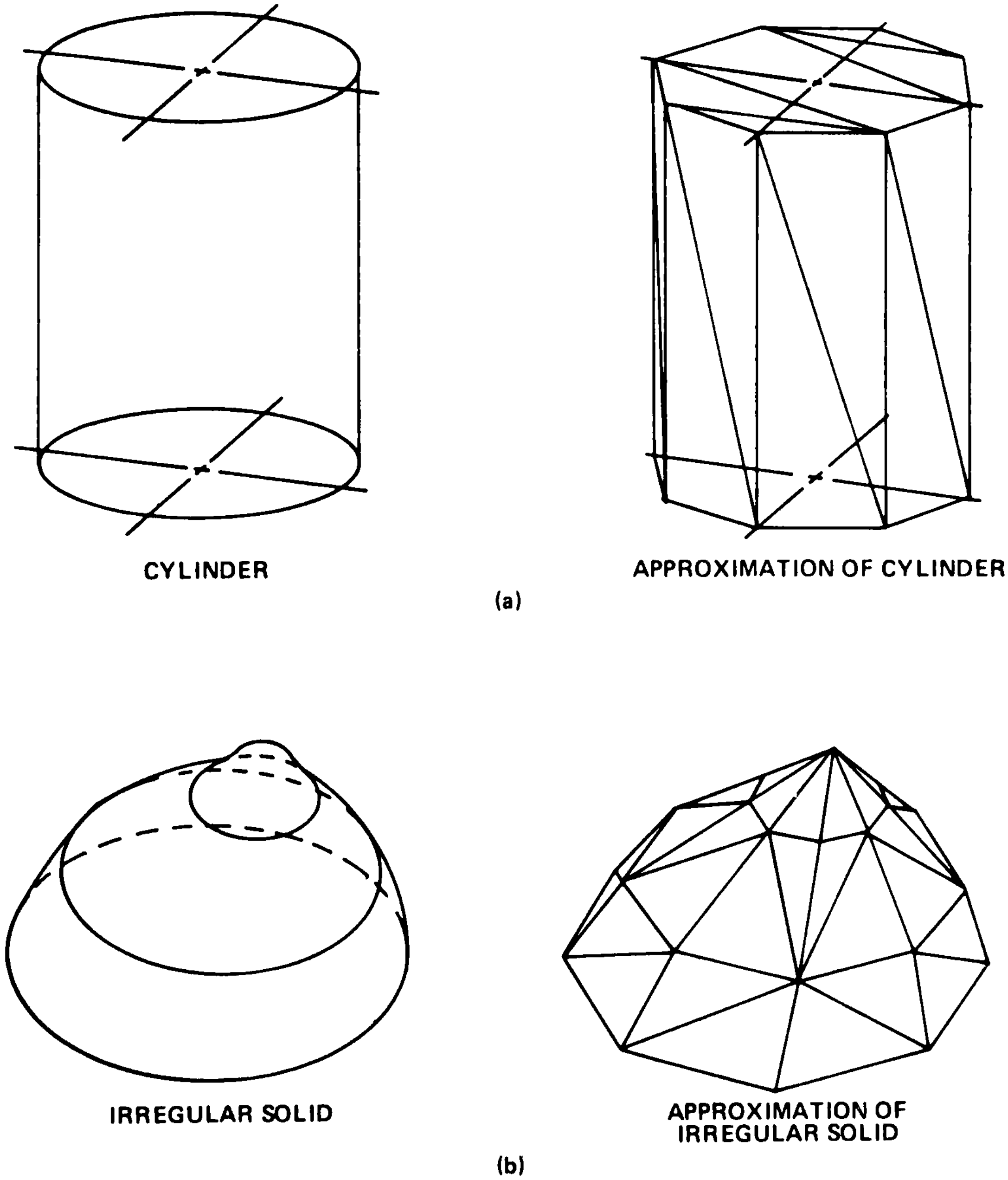

Figure 8. Approximation of Objects With Curved Surfaces

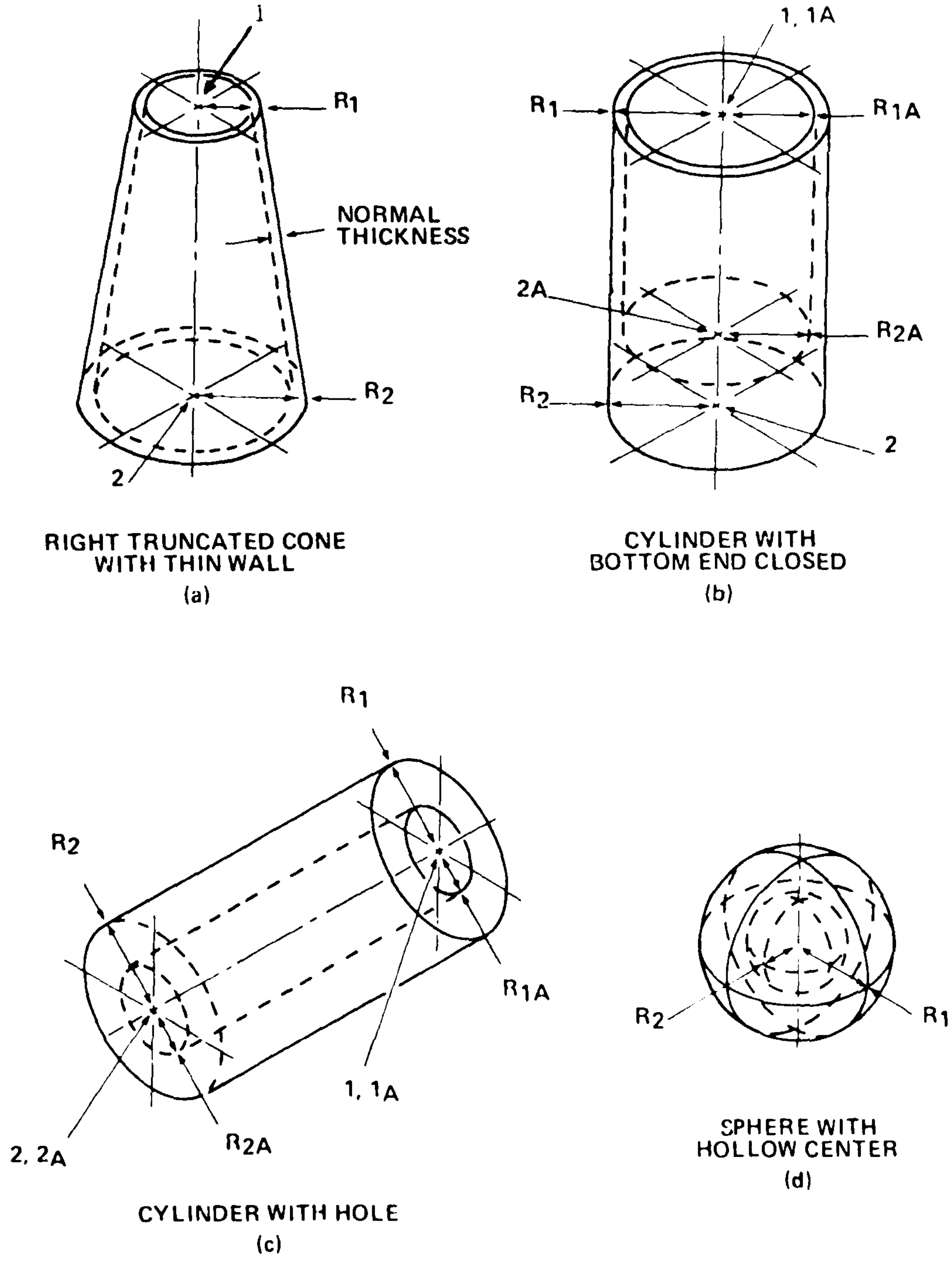

Figure 9 . Simplified Method of Describing Standard Hollow Shapes

axis end points 1A and 2A and radii R_{1A} and R_{2A}. The composite description is a hollow cylinder with wall thickness $R_1 - R_{1A}$, and a closed bottom end. Figure 9 (c), described in volume mode, also requires the description of two cylinders. Because axis end point sets are both equal, the composite description is a cylinder with a hole completely through its center. Figure 9 (d) depicts a hollow sphere, represented through volume subtraction by two spheres described in volume mode. The double description of the volume enclosed by R_2 essentially cancels that volume and creates a void.

An example of a fuel line described in rod mode is contained in Figure 10. For this example, the component is described as six segments and nine points.

6. CREATE TARGET MODEL FILE

This step, which consists of compiling component description into FASTGEN II input format, is best accomplished on a component-by-component basis using coordinate and radii data recorded on component sketches. The following paragraphs describe the major tasks associated with this step, which are:

- Coding component description data onto specially formatted keypunch forms
- Keypunching coded component data and ordering punched cards to create a complete target description card deck
- Preparing a binary blocked file from the target description card deck.

A blank FASTGEN II keypunch form is included in Appendix A of this document. Decimals printed on this form should be punched. Preparers of new FASTGEN II target models should recognize and take advantage of any automated techniques which reduce the overall target model file preparation effort. A number of techniques are available that were derived from recognized component location symmetry. Proven techniques include mirror imaging, rotation and translation, and the use of previously coded component descriptions. Each of these techniques are based on the premise that target components are described as points (and radii) relative to a selected coordinate system and that they can, therefore, be relocated to another target position by appropriately adjusting the original point coordinates. Preparers

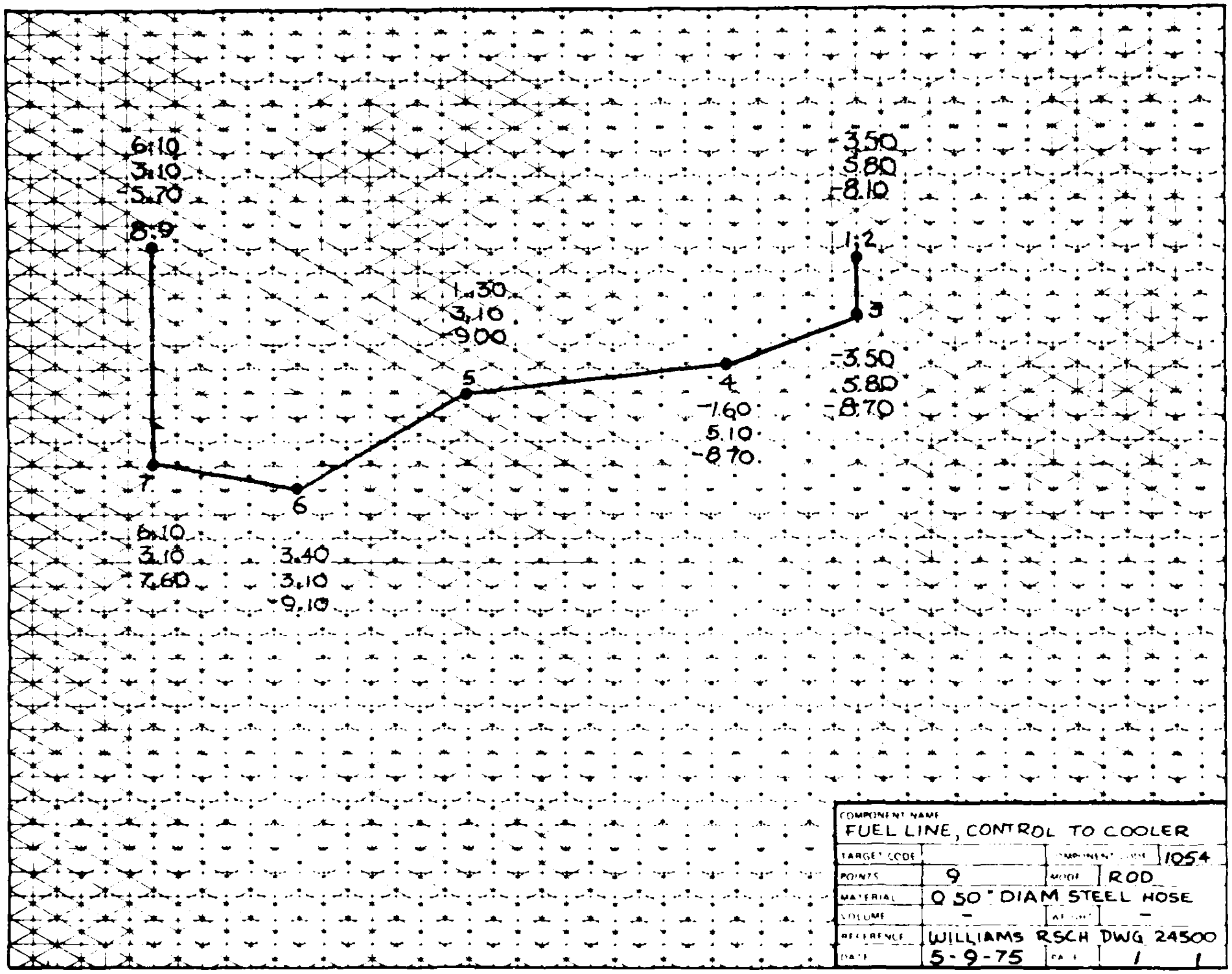

Figure 10. Rod Component Sketch and Coordinates for a Fuel Line

are forewarned to carefully establish the types of duplicative techniques which are applicable for the particular target. The most often used duplication technique for aircraft targets consists of mirror imaging major structural members such as entire wings, elevators, etc. Rotation and translation techniques have been used successfully for duplicating major sectors of entire engines on multi-engine aircraft. Using previously coded component data requires a detailed verification of description coordinates.

a. <u>Coding Component Description Data</u>

Each component point vertex is recorded on a single 80-column computer card. In addition to the coordinates, each card must contain a component identification code and a sequence number. The sequence number can be any increasing series of integers. These numbers are not recognized by the computer program and are used only for card deck organization. It is good practice to use sequence numbers such as 10, 20, 30, etc., to permit extra card insertion(s) when altering a component without complete resequencing.

The component identification code number contains five items of information, as follows:

± G NN S CCCC

- CCCC — Component Number
- S — Space Identification Code
- NN — Normal Thickness Code
- G — Geometric-Type Code
- ± — Plate/Volume Mode Code

Plate mode is represented by a preceeding negative sign (-), whereas volume mode is represented by a positive sign (+) or a blank. The geometric-type code defines the shape used to model the component segment. A zero denotes triangular approximation, a six denotes a sphere segment, an eight denotes a right circular truncated cone (or cylinder), and a nine denotes a rod component. The normal thickness of plate-mode components is entered in hundredths of an inch, and zeros are entered for volume-mode components. The space identification code defines the area of the target the

component must reside in. Space codes are used to facilitate debugging a target model and provide a means of altering vulnerability, depending upon the space surrounding the component. Space codes currently in use are given below for ground vehicles and aircraft.

GROUND VEHICLES	SPACE CODE	AIRCRAFT
Bulkheads (Plate Mode Only)	0	Bulkheads (Plate Mode Only)
Engine Compartment	1	Fuselage and Engine Pods
Crew Compartment	2	Cockpit
Cargo Compartment	3	Interior of Wings
Not Used	4	Vertical Fin and Elevators
Exterior	5	Exterior

A zero space code identifies a plate mode component which seperates two interior spaces (i.e., a Bulkhead). The last four digits contain a unique number for each component of the target. The first digit of this number must be zero for plate-mode components which define a space within the target. When no physical boundary exists between an interior space and the exterior (Space Code 5), a fictitious plate-mode component of zero thickness (phantom armor) must be included.

The card format for each point vertex of component segments described with the triangular approximation technique is:

X COORD	Y COORD	Z COORD	COMPONENT CODE	SEQUENCE NUMBER
±XXXX.XXX	±YYYY.YYY	±ZZZZ.ZZZ	±0NNSCCCC	II

An example code sheet for the triangular approximation of a heat exchanger is contained in Figure 11.

FASTGEN II COMPONENT CODE FORM

TARGET ____________ PAGE _ OF _

X - COORDINATE (OR RADIUS) 1–10	Y - COORDINATE (OR RADIUS) 11–20	Z - COORDINATE 21–30	COMPONENT CODE NUMBER 31–40	RECORD SEQUENCE NUMBER 41–50
27.00	6.20	0.20	19002	10
27.00	6.20	0.20	19002	20
27.00	-6.20	0.20	19002	30
24.10	6.20	0.20	19002	40
24.10	6.20	0.20	19002	50
24.10	-6.20	6.30	19002	60
27.00	-6.20	0.20	19002	70
27.00	-6.20	6.30	19002	80
27.00	6.20	0.20	19002	90
27.00	6.20	6.30	19002	100
24.10	6.20	0.20	19002	110
24.10	6.20	6.30	19002	120
24.10	-6.20	6.30	19002	130
27.00	6.20	6.30	19002	140
27.00	-6.20	6.30	19002	150
27.00	-6.20	6.30	19002	160

Figure 11. Code Sheet for Triangle Approximation of a Heat Exchanger (Volume Mode)

For cones and cylinders, each component segment is described by thrce input cards. Thc first two card records are identically formatted and describe the component axis end points. The format for each card is as follows:

X COORD	Y COORD	Z COORD	COMPONENT CODE	SEQUENCE NUMBER
±XXXX.XXX	±YYYY.YYY	±ZZZZ.ZZZZ	±8NNSCCCC	II

The code number composition is the same as for the triangle approximation method except that the component-type code equals eight.

The third cone/cylinder card record contains the radius of both end planes. The format for the third card is as follows:

FIRST END RADIUS	SECOND END RADIUS	COMPONENT CODE	SEQUENCE NUMBER
RR.RRR	SS.SSS	±8NNSCCCC	II

The first and second end radii card column locations correspond with the X- and Y-coordinate card column locations. An example code sheet for cone/cylinder and sphere component is contained in Figure 12.

The description of spherical-type component segments is similar to that for cones, but only two cards are required. The first contains the sphere centroid location; the second, the sphere radius. The component-type code for spheres is six.

Fuel lines, oil lines, control rods and cables, and electrical wiring can be modeled with rods by merely describing the component center-line and its radius. An example of a fuel line described in rod mode is contained in Figure 13. For this example, the component is described as six segments and nine points. Each of the points are formatted as follows:

FASTGEN II COMPONENT CODE FORM

TARGET ____________ PAGE __ OF __

X COORDINATE (OR RADIUS) (cols 1–10)	Y COORDINATE (OR RADIUS) (cols 11–20)	Z COORDINATE (cols 21–30)	COMPONENT CODE NUMBER (cols 31–40)	RECORD SEQUENCE NUMBER (cols 41–50)	
-42.89	0.00	7.66	800111003	10	A
-46.54	0.00	7.08	800111003	20	A
4.30	4.30	0.00	800111003	30	A
-42.89	0.00	7.66	800111003	40	A
-46.54	0.00	7.08	800111003	50	A
2.10	3.00	0.00	800111003	60	A
-43.77	0.00	7.52	600111044	10	B
6.00	0.00	0.00	600111044	20	B
-43.77	0.00	7.52	600111044	30	B
5.75	0.00	0.00	600111044	40	B

A Blades/Stators, Low Pressure Compressor (1003)

B Oxygen Bottle (1044)

Figure 12. Code Sheet Illustrating Volume Subtraction for Cone/Cylinder and Sphere-Type Components

FASTGEN II COMPONENT CODE FORM

TARGET ________ PAGE __ OF __

X COORDINATE (OR RADIUS) 1–10	Y COORDINATE (OR RADIUS) 11–20	Z COORDINATE 21–30	COMPONENT CODE NUMBER 31–40	RECORD SEQUENCE NUMBER 41–50
-52.21	5.80	-4.43	-91211054	10
-52.21	5.80	-4.43	-91211054	20
-52.12	5.80	-5.02	-91211054	30
-50.24	5.10	-4.72	-91211054	40
-47.33	3.10	-4.57	-91211054	50
-45.25	3.10	-4.24	-91211054	60
-42.59	3.10	-3.81	-91211054	70
-43.10	3.10	-0.56	-91211054	80
-43.10	3.10	-0.56	-91211054	90

Figure 13. Code Sheet Illustrating a Rod-Type Component (1054)

X COORD	Y COORD	Z COORD	COMPONENT CODE	SEQUENCE NUMBER
±XXXX.XXX	±YYYY.YYY	±ZZZZ.ZZZ	-9RRSCCCC	II

Rod-mode components are defined with component type nine. Component code number spaces labeled RR are reserved for the respective rod segment radius, in hundreths of an inch. Note that a minus sign must preceed the component type.

b. Composite Target Card Deck

The final target description card deck consists of all component card sets. There is no required component set ordering scheme. Experience has proven, however, that component cards are best ordered according to their respective four-digit component identification code number. FASTGEN II does require that all cards for each component segment be located together and in their proper sequential order.

c. Binary Target Description File

The FASTGEN II program documented in this report required that target description data reside on Logical Tape 9 in binary blocked format. This requires that the target description card deck be read and converted to its binary equivalent before FASTGEN II execution.

7. VALIDATE TARGET MODEL

Because of the intricate nature of the target description preparation process, there will always be some errors which require correction before a production quality target description is achieved. The preparer should accept this eventuality and resign himself to approaching the error correction process as an absolute requirement.

The FASTGEN II program and its built-in error diagnostic capabilities represents the single-most effective tool for validating the target description model. To control the magnitude of error diagnostic printout, initial validation should begin by running one attack aspect angle with a

large grid cell size. For exceptionally large targets such as the B-52, validation should begin by considering individual target sections using the target envelope option.

As initial errors are identified and corrected, other attack aspects can be evaluated, the grid cell size can be reduced, and additional target sectors can be processed. Experience has proven that an initial macro approach serves to limit encountered errors for large obvious target description mistakes, and permits an incremental approach to overall error correction.

As grid cell size is reduced and/or more target sections are included, additional errors may occur. Often these errors will be more difficult to alleviate and require a more detailed analysis to determine their cause. For these cases, it is frequently convenient to perform the analysis in the original coordinate system. The required translation and rotation can be appropriately performed using programmable hand calculators or a minicomputer such as the WANG 700.

During the validation process, it is frequently advantageous to utilize perspective and cross-sectional plot routines to depict target components as viewed by the computer. Plot routines have been employed to illustrate components and trace shotlines through a target model. The latter is accomplished by plotting the distances through components for all shotlines which pass through a particular row or column of grid cells.

APPENDIX B

TARGET MODEL PREPARATION FOR LMP-3

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TARGET MODEL PREPARATION FOR LMP-3

The target description includes those items needed in the computer program LMP-3 to implement the various calculations. These calculations serve to determine whether the terminal effects of the threat should result in incapacitating damage to critical aircraft components, and whether the failure of those components will result in aircraft subsystem malfunctions which could affect aircraft performance in each of several modes. The five modes of aircraft performance are related to performance of the assigned mission and to availability for another mission. These are:

1. Mission aborted - aircraft lost,
2. Mission aborted - aircraft returned to base - repairs required prior to next mission,
3. Mission completed - aircraft lost,
4. Mission completed - aircraft returned to base - repairs required prior to next mission, and
5. Mission completed - aircraft returned to base - aircraft available for next mission.

The <u>external</u> surfaces (skins) of the aircraft are described in terms of geometry as polyhedra and in terms of ballistic resistance as an equivalent thickness of aluminum and an equivalent density. These are used simply to allow computation of residual fragment momentum for subsequent impacts upon critical components. Perforations in skins are not a criteria for need for repair.

The criteria for mission completion, aircraft return, and need for repair are primarily the number of damaging fragment impacts upon critical components. Since an aircraft contains a number of systems (propulsion, avionics, flight controls, hydraulic, etc., but also including the pilot) which must function properly in order for that aircraft to perform a mission, for that aircraft to return to its base, and for that aircraft to be available for a subsequent mission, these critical systems are monitored for ballistic damage. These systems are composed of one or more components. Since these components are usually located within the aircraft, they are termed <u>internal</u>. The principal damaging agent is a high-velocity fragment. These critical components are described as one or more line segments with an associated presented area which is vulnerable to the fragment impact

and an associated thickness of aluminum which must be penetrated to obtain crippling damage. In addition to damage from impacting fragments, the program treats damage from blast.

The treatment of blast damage differs slightly when the burst is internal rather than external, and also differs when certain components/ subsystems which occupy greater volumes are concerned.

The details of the target description necessary to provide inputs for these computations follow.

EXTERNAL GEOMETRIC DESCRIPTION

The external target description is designed to describe the target's external surfaces by means of a number of simple bodies. Individual bodies represented by polyhedra with a suitable number of corners are selected to have a density which is as homogeneous as possible.

Skin thickness and internal densities (which are used to indicate fragment retardation during penetration of the structure) are indicated for the various polyhedra making up the target.

Polyhedra

The polyhedra must be convex with an even number of corners. Not more than twenty corners can be used and the order in which the corners are given is important. Two basic surfaces have to be defined and the number of corners are as given in this example.

The surfaces (planes) are defined by three corners (points), for example:

Surface	Corners
1	1,2,6
2	2,3,7
3	3,4,8
4	4,5,9
5	5,10,6
6	1,2,3
7	6,7,8

If it is possible it is good to have the corners defining a surface as widely separated as possible to reduce the effect of point location designation error. The coordinates of each corner are usually given with an accuracy of 1 cm.

Two levels of polyhedra are available. One (or several) second-level polyhedron(s) can be surrounded by a first-level one. They must, however, be completely surrounded. No intersections between any polyhedra are allowed.

Structure's Fragment Retardation Properties

These functions are used to calculate the probability of the fragments in question to reach a critical component.

Using a computer program where investigations have been carried out in which the input data are an extremely detailed description of the airplane's structure, and where the result is obtained in terms of distributions indicating the structure's "inhibiting" effects upon the fragment's momentum as a function of the distance traveled by the fragments, for variour parts of the aircraft. This distribution has been found to be logarithmically normal (with satisfactory accuracy), and its parameters are expressed as: Amount of momentum per surface unit.

For cubic steel fragments (10 mm on a side, directed against aircraft J 35), the momentum per impacted area (Y) is calculated as that which the fragment required in order to penetrate a certain distance. The computations are carried out for a large number of fragments and the results are processed statistically and presented in diagram form for various penetration intervals in various parts of the aircraft (mean values and variance for ℓn Y). These values have been used to give the retardation functions even for other targets and fragments.

Assuming that the polyhedra's fragment relationship properties are determined by the skin and the inner density, the mean value E(Y) is a linear function of the depth of penetration, $E = a + bx$, where intercept a at the origin is proportional to the skin thickness t (mm dural), and inclination b is proportional to the internal density ρ. Empirically, we know that $a = K_1 \cdot t$ and $b = K_2 \cdot \rho$ for the fuselage, and that $b = k_3 \cdot \rho$ for the wings. The internal density ρ for a polyhedron is calculated as:

$$\rho = \frac{\text{total mass - mass of the skin}}{\text{volume}}$$

and the thickness t if the material is not dural

$$t = \frac{\text{thickness of plate x density of plate}}{\text{density of dural}}$$

In the original calculation of the fragment-retarding property we have assumed $\ell n\ Y = N(m,\sigma)$. The variance is evident in that σ is independent of the depth of penetration, but varies with the internal density ρ from polyhedron to polyhedron. In approximating m by means of a straight line, we have assumed that $E(Y) = a + bx$ and that $b \approx \rho$ so that σ should be a function of $\ell n\ \rho$.

Fuselage: $\sigma = K_5 + K_6 \times \ell n\ \rho$

Wing: $\sigma = K_7 + K_6 \times \ell n\ \rho$

This model for the fragments retardation capability as a function of skin thickness and internal density has been checked using the J 35 (Draken or Dragon) and a relative deviation of 10 percent was observed. However, these functions are calculated only for one type of fragment (steel cubes) and if other fragments are concerned, their weight has to be changed to the weight of a steel cube with the same capability of perforation as the fragment in question. This is accomplished in the threat description.

In order to correct for the effect of blast where the burst is external to the target but within a specific distance (RADIE or Radius, which is a function of the threat size), the skin thicknesses are reduced by an input fraction (normally 0.50). Where the burst is within the target, the skin thickness is reduced by a different value (normally either 0.90 or 0.50). The reduction factors are functions of the size of the warhead and are given with the other data describing the warhead.

Input Variables

Subroutine INIMPO

NPOL Total number of polyhedra
Maximum 250

NRPOL(i) i = 1, NPOL
Type of polyhedron
NRPOL = 0. A first or a second level polyhedron which does not surround any other polyhedron or is surrounded by another polyhedron.
NRPOL = a number. The total number of polyhedra within this first level polyhedron.
NRPOL = the reference number of the polyhedron (= ISLA).

A second-level polyhedron that is within another polyhedron. In the input stream this kind of polyhedron has to come immediately after the polyhedron that surrounds it.

NRR(i)	i = 1, NPOL A number to identify the equation that is used to calculate the penetration of fragments in this polyhedron. See NGM.
LH	Number of corners. Maximum 20.
ISLA	Reference number.
RHRN(j,i)	j = 1, 3. i = 1, LH. Coordinates of the corner given in centimeters in the coordinate system of the target.
NGM	Number of equation for calculating the penetration of the fragments. Maximum 107.
NGS	Number of values to describe each equation. Maximum 10, but have never used anything else but 2.
GMED(j,i)	j = 1, NGS. i = 1, NGM. (see Figure B-1) The mean value [E(Y)] of the distribution that describes the penetration of fragments. E(Y) is a function of the distance within the target that the fragment has to travel and the index j is used to give E(Y) for different distances. The values are given in grams x centimeters/seconds x centimeters^2.
GAVS(j,i)	j = 1, NGS. i = 1, NGM. The distances for which the mean values are given. We have used 0 and 1000 centimeters.
GSPR(j,i)	j = 1, NGS. i = 1, NGM. The standard deviation which, however, is assumed to be independent of the distance.

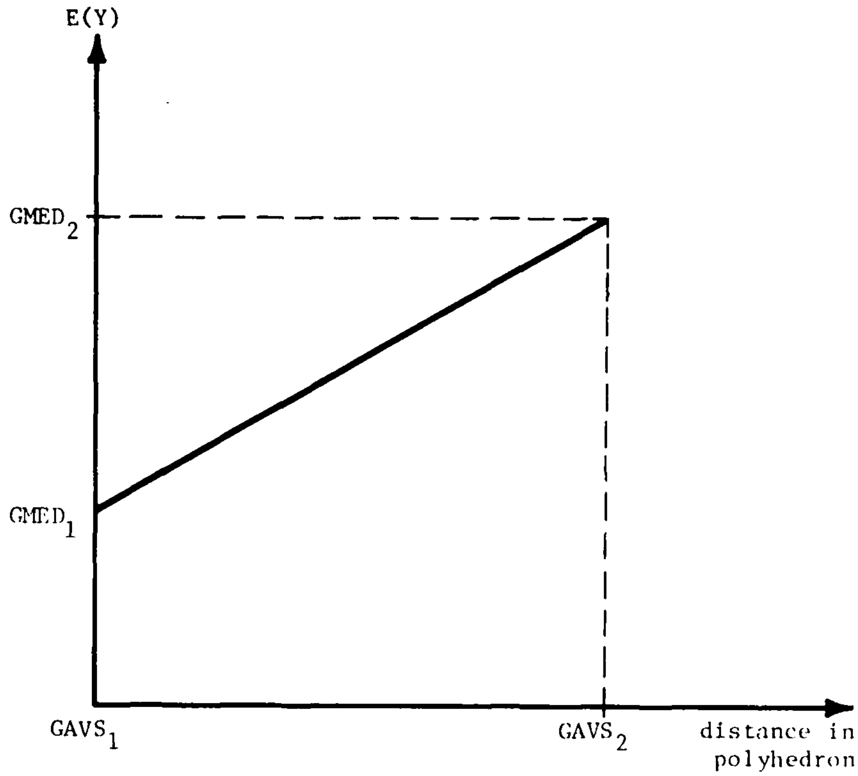

Figure B-1. Fragment Penetration Distribution Function

Example

Polyhedra

Total number of polyhedra NPOL

Type of Polyhedron NRPOL

Identification of equation used for calculating fragments penetrating NRR

Total number of corners LH

Reference number ISLA

36

0	1	10	1

200.	0.	31.2	200.	0.	50.7
377.	40.	-40.	377.	40.	58.
546.	60.	-108.	546.	60.	65.
546.	-60.	-108.	546.	-60.	65.
377.	-40.	-40.	377.	-40.	58.

2	2	16	3

546.	25.	65.	785.	25.	66.
546.	59.	42.	785.	73.	33.
546.	59.	-41.	785.	73.	-33.
546.	17.	-80.	785.	16.	-86.
546.	-17.	-80.	785.	-16.	-86.
546.	-59.	-41.	785.	-73.	-33.
546.	-59.	42.	785.	-73.	33.
546.	-25.	65.	785.	-25.	66.

15	19	16	15

549.	7.	27.	549.	-7.	27.
558.	7.	7.	558.	-7.	7.
578.	7.	-1.	578.	-7.	-1.
598.	7.	7.	598.	-7.	7.
606.	7.	27.	606.	-7.	27.
598.	7.	47.	598.	-7.	47.
578.	7.	56.	578.	-7.	56.
558.	7.	47.	558.	-7.	47.

16	11	8	16

605.	6.	34.	706.	6.	50.
605.	-6.	34.	706.	-6.	50.
607.	-6.	23.	708.	-6.	39.
607.	6.	23.	708.	6.	39.

Coordinates X, Y, Z of the corners 1 through 4 describing one of the base surfaces. RHRN.

Coordinates X, Y, Z of the corners 5 through 8 describing the other base surface.

In this example, the first polyhedron is not involved in any other polyhedra. The second polyhedron is a first-level one surrounding two other polyhedra, namely, polyhedron 15 and 16.

Fragment Retardation Functions

Total number of equations NGM

Number of values for each equation NGS

22

2	2	2	2	2	2	2	2
3.6	E5	0.0	1.086	10.86	E6	1000.	1.086
1.35	E5	0.0	1.127	14.235	E6	1000.	1.127
1.35	E5	0.0	0.688	2.735	E6	1000.	0.688
1.35	E5	0.0	1.028	7.085	E6	1000.	1.028
3.3	E5	0.0	1.064	15.33	E6	1000.	1.064
$GMED_1$		$GAVS_1$	$GSPR_1$	$GMED_2$		$GAVS_2$	$GSPR_2$

Each line is describing a new equation. The first five equations are as follows:

$GMED_1$ = mean value of the distribution at a given distance

$GAVS_1$ = the first distance for which the values are given

$GSPR_1$ = the standard deviation at the first distance

$GMED_2$ = the same as the first but given for the second distance

$GAVS_2$ = the second distance

$GSPR_2$ = the same value as the third as the standard deviation is independent of the distance

INTERNAL DESCRIPTION

The internal target description is designed to determine the degradation in performance and condition occurring in aircraft critical systems as a consequence of the damage suffered by various components struck by fragments (by means of functional analysis).

The target is divided into a number of functional systems which are evaluated with regard to both design and function. Special interest is directed toward redundant systems. The components of a functional system are analyzed assuming that the system's function is affected by single-fragment impacts. This analysis has been carried out in cooperation with designers and manufacturing personnel, and based upon experience from testing of the effects from fragment impacts. When fragments strike the

components of a functional system, various types of damage occur, subjecting the system in question to a failure to function. In principle, our analyses include all of the critical components in the target, and give, for each possible component damage, the failure modes which would occur. Those components of a functional system which, when they are damaged, cause the same kind of failure are gathered into subsystems or systems.

Subsystem

With regard to airplanes and helicopters, we must keep in mind that the pilot will deal with a failure mode on the basis of his perception of it so that the failure modes are defined as perceived by the pilot.

Evaluations of the consequences of failure modes involved in the aircraft analysis must be related to one or more defined missions, which include tactical and environmental data for the aircraft in question.

- Tactical data
  - Type of mission
  - Armament alternatives
  - Distance to target specified in mission
  - Distance to home base
  - Altitude
  - Velocity
  - Additional performance data
- Environmental data
  - Day or night
  - Meteorological conditions
  - Visibility
  - Season

The mission serves as the basis for the evaluation of the failure modes of aircraft. These evaluations are made following interviews with pilots (when the target in question is an airplane or helicopter) or designers (when the target is a missile). A failure mode is related to an effect criterion which is defined.

If the target is an airplane or a helicopter, the following resultant events may be used as effect criteria:

1. Mission aborted - airplane/helicopter lost.

2. Mission aborted - airplane/helicopter returns to base - subsequent missions delayed.
3. Mission accomplished - airplane/helicopter lost.
4. Mission accomplished - airplane/helicopter returns to base - subsequent missions delayed until damage is repaired.

Even if it is possible for the aircraft to return to base, it will have to undergo repairs, which will delay the execution of a new mission. The time elapsed and labor hours required to affect these repairs are not calculated in LMP-3.

The results of the interviews are expressed as a probability distribution for the four resultant events, for each defined system damage or failure. The sum of these four probabilities is one as they are describing what will happen if the damage occurs. This way of describing the damage means that the same component can affect more than one subsystem. In that case, the component is also described several times (once in each subsystem). It also means that the failure mode occurs independent of which one of the components that is damaged. See component description.

The subsystems are divided into two categories:

1. Systems which are rendered inoperable by the impact of one fragment with sufficient momentum per unit area to penetrate a given thickness of material (for example, cables, lines, pipes); and
2. Systems in which the kill probability increases with the number of hits (for example, windscreen, engine, fuel cells).

The subsystems are considered to be independent but they can also be marked as redundant. In that case, at least one component in each system has to be disabled by fragment impacts before the failure occurs.

Components

The critical components involved in the target's functional systems are described geometrically by allowing each component to be represented by one or more line segments oriented in the target's longitudinal direction (parallel to the x axis). The line segments are generally not longer than 1 m and if the component is extended in a direction other than longitudinal, the line segments are usually described for each 0.5 meter, Figure B-2.

Each line segment is ascribed a ballistic resistance, which is a measure of the residual momentum which a fragment must have in order to damage

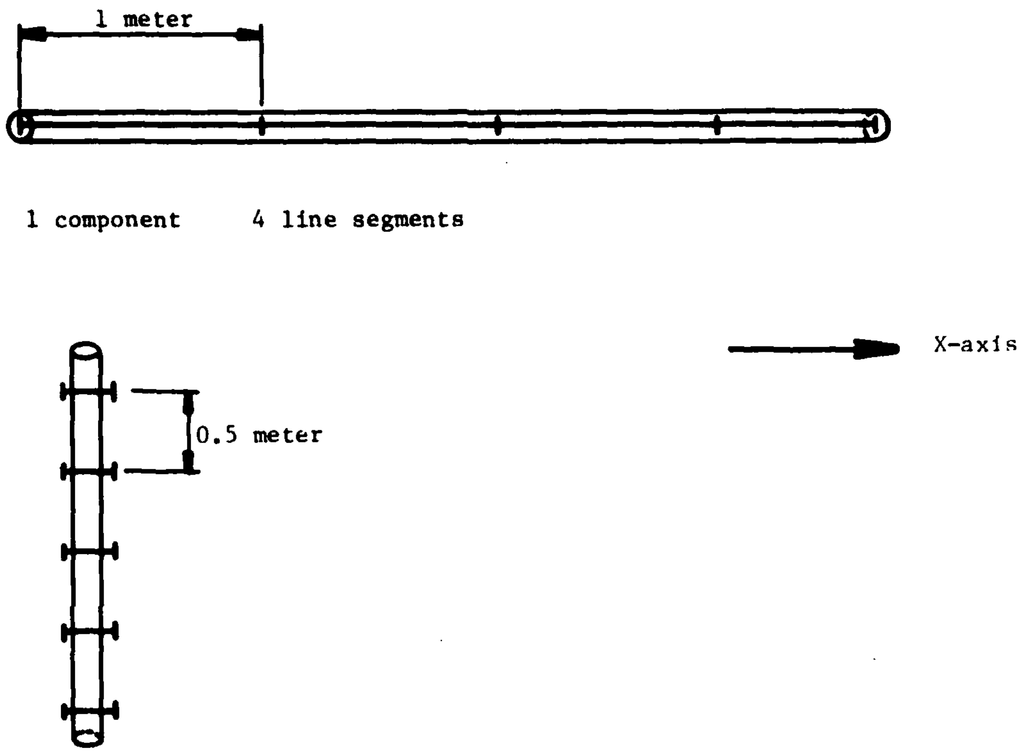

Figure B-2. Line Segment Breakdown

the component in question. For example, the ballistic resistance for a fuel tank corresponds to the tank wall thickness. If the fragment perforates this wall, leakage and, perhaps, fire will occur. Incidence of fire is not treated per se; the analyst would account for fire reduction features by using a lesser effect criteria probability for a protected fuel cell than he would for an unprotected one. The ballistic resistance is given in millimeters of dural, and if the component is made of something else, its thickness is equated to dural proportional to its density. "Dural" is used as a generic term for aluminum; ballistic penetration tests in Sweden were conducted using an aluminum alloy, SIS4338.06, similar to Al 2014-T6.

Each line segment is also ascribed an area. This area is the average of the areas shown of the real component in different directions if the component is described by one line segment and if the whole component is vulnerable to the fragments in question. The descriptions are originally made for 1 cm^3 steel fragments and extensions to other fragments are made by changing the probabilities of the subsystems. If, let us say, just 50 percent of the component is vulnerable, then this area is also 50 percent of the whole area. If the component is described by more than one line segment, this area is divided by the number of line segments and each line segment is ascribed the same amount of the total area. If a component is described in more than one subsystem, the sum of the areas still cannot be more than the real total area.

Depending on the length of the component compared to the thickness, the area is calculated in different ways. Given are the maximum value of the mean value of the largest and the smallest surface or the largest surface times cos 45°.

A code assigned to each line segment can be used to account for the influence of the target skin (one of the polyhedra) in reducing a fragment's momentum, hence, penetration or damage capability, when calculating the probability of the fragment reaching that line segment and damaging the component thereby requested.

The rotor blades of a helicopter are treated as a component. The rotor blades are, however, also described by a cylinder, and the area shown against the burst point of that cylinder gives the area of the component. This cylinder normally has a thickness equal to the actual blade but the diameter is not necessarily the tip-to-tip distance.

One may reduce costs by not making all the calculations for every line segment. The areas of consecutive line segments within the same subsystem are added up to a given limit and when this limit is reached, the sum of the areas are given to the last line segment and the aforementioned calculations are made for this line segment.

Input Variables

Subroutine INIM

MJS — Total number of subsystems - maximum 127

KMA(i) — i = 1, MJS.
Total number of line segments within a subsystem.

MHS — Number of effect criteria considered - an integer from 1 to 5.

ISLA — Reference number of the subsystem or the line segment.

MPR(i) — i = 1, MJS.
Code to give the type of subsystem.
In existing target descriptions, the pilots and the passengers are given a specific code, but that is not used in the program any longer.
MPR < 100 a subsystem of category 1.
MPR $\geq$ 100 a subsystem of category 2.
For redundant subsystems the last digit of MPR has to be the same.

BPR(j,i) — j = 1, MHS + 1. i = 1, MJS.
Effect criteria for the subsystem.
For subsystems of category 1, BPR is defined as

$$BPR_i = P(\text{Event } i/\text{at least 1 hit})$$

and for category 2

$$BPR_i = P(\text{Event } i/\text{exactly 1 hit})$$

X1, Y1, Z1 — Coordinates of one of the end points of a line segment. Given in centimeters in the coordinate system of the target.

X2 — As the lines are parallel to the X-axis only the X-coordinate is given for the trailing end of the line.

YA(j1) — j1 = 1, total number of line segments. Maximum 1200.
Area of line segment (component) vulnerable to fragment impact given in centimeters^2.

TjL(jl)	jl = 1, total number of line segments. Resistance of line segment (component) given in mm dural.
TL(jl)	jl = 1, total number of line segments. Code to tell if the line segment is not protected of a certain polyhedron. If that is the case JL = the number of that polyhedron and in all other cases JL = 0.
AB1, AB2	Constants to be used in a penetration equation. $AB1 = 0.25 \times 10^{-6} \frac{cm^2 \times sec}{gram}$ $AB2 = 0.218 \times 10^{-5} \frac{cm^2 \times sec}{gram}$
NROT	Total number of rotors, maximum of 2 allowed in LMP-3.
ROTMTT (K,L)	K = 1, 3; L = 1, NROT. Coordinates of center of rotor blades given in centimeters in the coordinate system of the target.
ROTAXL (K,L)	K = 1, 3; L = 1, NROT. Direction of axle or rotor.
TVRYTA (L)	L = 1, NROT. Cross-sectional area presented by a rotor in centimeters^2.
TOPYTA (L)	L = 1, NROT. Top area presented of rotor in centimeters^2.
LL	Total number of line segments to describe one rotor. Maximum 20.
JRAD (L1, L)	L1 = 1, LL; L = 1, NROT. Reference numbers of the line segments describing the rotor.
YTOL	The limit which the sum of line segment areas must be equal or exceed before a contribution calculation go on. Given in meters^2 and a value of that has been used is 0.005 m^2.

Example

Reference number of the subsystem. ISLA.

Code to tell what kind of subsystem. MPR.

Probability for effect criterion 1. BRR(1).

Probability for effect criterion 2. BPR(2).

Probability for effect criterion 3. BPR(3).

Probability for effect criterion 4. BPR(4).

01	100	.05		.1	.85			
01		447.	9.	-57.	479.	123.	5.	0.
01		447.	-9.	-57.	479.	123.	5.	0.
01		448.	16.	-50.	480.	123.	5.	0.
01		448.	-16.	-50.	480.	123.	5.	0.
01		452.	24.	-41.	484.	123.	5.	0.
01		452.	-24.	-41.	484.	123.	5.	0.
01		416.	11.	-39.	448.	123.	5.	0.
01		416.	-11.	-39.	448.	123.	5.	0.
		X_1	Y_1	Z_1	X_2			

Code for calculating fragment penetration JL.

Equivalent component thickness (mm dural). The fragment must penetrate this much aluminum after reaching the component in order to cause damage. TJL.

Area of component vulnerable to fragment impact (cm^2) adjusted to each line segment. YA.

Coordinates to describe the line segments. As they are parallel to the X-axis, you only need one coordinate for one of the end points. X_1, Y_1, Z_1 are coordinates of the leading end of the component line segment. X_2, Y_1, Z_1 are the coordinates of the trailing end of the line.

Reference numbers of the components. ISLA.

BLAST DAMAGE

Blast damage is treated using three factors, which are:

1. If the burst is external to the aircraft and is within a given distance or if the burst is internal to the aircraft, then the parameters used to compute the momentum reduction factor for fragments impacting critical components within given polyhedra are changed;

2. If a line segment representing a given critical component falls within the blast effect ellipsoid for the warhead, 1000 effective fragment impacts are added to the line segment; and

3. If the warhead burst point is within the volume of specific type components (fuel tanks, cabin or cockpit), then these are treated as separate subsystems with their own effect criteria.

Therefore, to handle the blast effect, the volumes describing those components have to be added to the target descriptions.

These volumes can be rectangular parallelepipeds or right cylinders. The effect contribution from blast in these components is added to the overall system effect as an additional subsystem and may contribute to Event 1, 2 and/or 3. Note that the contribution from the subsystem is a contribution to the total effect. These do not affect the fragment impact upon line segment contributions to the mission effect for the same components, but are additive thereto.

The size of the volumes is not a function of the size of the warhead. Examples of components which have been described as volumes are cabin or cockpit, inlet, fuel cells, and engine.

Input Variables

Subroutine INLAES in Part II of LMP-3.

NLAD	Total number of parallelepipeds. Maximum 10.
FLAD (i,j,K)	i = 1, 2; j = 1, 3; K = 1, NLAD. Coordinates of the corners given in meters in the coordinate system of the target.
PL (L, K)	L = 1, MHS + 1; K = 1, NLAD. Kill criteria (compare BPR for line segments).
NCYL	Total number of cylinders. Maximum 5.

FCYL (i,j,K)	i = 1, 3; j = 1, 3; K = 1, NCYL. For j = 1, i gives the X, Y, Z coordinates (in meters) for the center point. In j = 2, i gives the X, Y, Z coordinates in the direction of the axis. For j = 3, i(1) gives half the lengths of the axis (in meters), i(2) gives the radii (in meters), and i(3) is dummy.
PC (L,K)	L = 1, MHS + 1; K = 1, NCYL. Effect criteria.

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